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# Development of a Minimum Performance Standard for Aircraft Cargo Compartment Gaseous Fire Suppression Systems


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16. Abstract

This report documents the test results of the testing conducted during the development of a minimum performance standard for aircraft cargo compartment gaseous fire suppression systems. It also includes the final version of the standard. The development work was performed in conjunction with the International Halon Replacement Working Group.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| CFM | Cubic Foot per Minute |
| CMM | Cubic Meter per Minute |
| DC | Direct Current |
| EPA | Environmental Protection Agency |
| FAA | Federal Aviation Administration |
| FAR | Federal Aviation Regulations |
| GWP | Global Warming Potential |
| IHRWG | International Halon Replacement Working Group |
| JAR | Joint Airworthiness Requirements |
| MPS | Minimum Performance Standard |
| ODP | Ozone Depletion Potential |
| SNAP | Significant New Alternatives Policy Program |
| VAC | Alternating Current Voltage |

# EXECUTIVE SUMMARY

This report documents the testing program that was commissioned by the International Halon Replacement Working Group (IHRWG) to develop the minimum performance standard for aircraft cargo compartment built-in fire suppression systems. The evaluation tests were conducted at the Federal Aviation Administration (FAA) William J. Hughes Technical Center in a modified DC-10 aircraft. The results from these tests, based on the Halon 1301 performance under well-defined cargo fire scenarios, were used to define the acceptance criteria that will be used to certify alternate gaseous extinguishing agents for aircraft cargo compartment fire protection.

Four different fire test scenarios were specified in the standard developed by the IHRWG; bulk-load fire, containerized fire, flammable liquid fire (surface burning), and an aerosol can explosion. The deep-seated fire scenarios (bulk load and containerized load) used shredded paper loosely packed in cardboard boxes to simulate the combustible fire load. The difference between these two test scenarios was that in the containerized fire load the boxes were stacked inside a LD3 container, while in the bulk-load fire scenario the boxes were loaded directly into the cargo compartment. The fuel used in the surface burning tests was 0.5 U.S gallon (1.89 liters) of Jet A fuel. The aerosol explosion tests were executed by using an aerosol can simulator containing a flammable/explosive mixture of propane, alcohol, and water. This mixture was ignited when it was exposed to an arc from sparking electrodes.

Baseline tests under each of these fire scenarios were conducted to establish the conditions when no extinguishing agent was used. These worst-case test conditions provided data that were used to highlight the performance of Halon 1301 when discharged in the compartment. When Halon 1301 was used, it totally flooded the compartment providing an initial volumetric concentration of 5% or higher and extinguishing open flames. During the deep-seated fires, a closed-loop-metered system was activated in order to maintain a minimum average volumetric concentration of 3% and protect the compartment for the duration of the 30-minute test. Test results showed that the combination of extinguishing systems were capable of controlling the deep-seated fires but as expected did not extinguish them. In the case of flammable liquid fires, Halon 1301 completely extinguished them in less than 45 seconds. Halon 1301 was also capable of inerting the aircraft cargo compartment when exposed to explosive mixtures of hydrocarbons. A minimum of 3%, by volume, was sufficient to inert the cargo bay. Table 3 summarizes the results obtained during this program.

Appendix A presents the Minimum Performance Standard for Aircraft Cargo Compartment Gaseous Fire Suppression Systems developed by IHRWG. This standard defines the tests needed to determine the performance of a halon replacement fire protection system designed to be installed onboard an aircraft cargo compartment.

## 1. INTRODUCTION.

### 1.1 OBJECTIVES.

Develop a minimum performance standard for testing replacement agents for equivalent performance to Halon 1301 in aircraft cargo compartment fire suppression systems. This developmental work was sponsored by the Federal Aviation Administration (FAA) in conjunction with the International Halon Replacement Working Group.

### 1.2 BACKGROUND.

Federal Aviation Regulations (FAR) and Joint Airworthiness Requirements (JAR) 25.857 contains the classifications for aircraft cargo compartments. After March 2001, all of the inaccessible below-floor cargo compartments on passenger carrying aircraft regulated by the FAA will be Class C cargo compartments. The requirements for Class C cargo compartments found in FAR/JAR 25.857 are as follows:

A Class C cargo or baggage compartment is one not meeting the requirements for either a Class A or B compartment but in which—

a. there is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station;

b. there is an approved built-in fire-extinguishing or suppression system controllable from the cockpit;

c. there are means to exclude hazardous quantities of smoke, flames, or extinguishing agent, from any compartment occupied by the crew or passengers;

d. there are means to control ventilation and drafts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment.

FAR/JAR 25.851 contains regulations concerning fire extinguishers. The following is the section of that regulation applicable to built-in fire extinguishers.

"(b) Built-in fire extinguishers. If a built-in fire extinguisher is provided—

(1) Each built-in fire extinguishing system must be installed so that—

(i) No extinguishing agent likely to enter personnel compartments will be hazardous to the occupants; and

(ii) No discharge of the extinguisher can cause structural damage.

(2) The capacity of each required built-in fire extinguishing system must be adequate for any fire likely to occur in the compartment where used, considering the volume of the compartment and the ventilation rate."

Although the regulations specify fire-extinguishing systems, it is understood by regulators and industry that the currently approved cargo compartment systems are more accurately referred to as fire suppression systems.

In the past, the aircraft industry has selected Halon 1301 total flood fire suppression systems as the most effective systems for complying with the regulations. However, halons have been identified as substances that contribute to the depletion of stratospheric ozone. For that reason, the production of halon was banned effective January 1994 by all countries that signed the Montreal Protocol. The signatories to that agreement included most of the developed world. Subsequent amendments to the Montreal Protocol have further restricted the use and transportation of existing halons. Although large quantities of halon currently exist, at some point the use of halon extinguishers and suppression systems on aircraft will no longer be viable.

IHRWG Task Group 9 was organized to develop a minimum performance standard (MPS) for aircraft cargo compartment built-in fire suppression systems. A primary objective was to develop a testing program to evaluate and characterize the performance of Halon 1301 when discharged into a compartment undergoing the fire scenarios specified in the standard. This document reports the findings of the tests conducted. The data collected from this program was used to define the acceptance criteria in the MPS contained in appendix A for gaseous replacement agents. At this time nongaseous suppression systems will be evaluated on a case-by-case basis depending on the unique characteristics of the system.

## 2. TEST SETUP AND INSTRUMENTATION.

### 2.1 TEST ARTICLE.

The fire tests were conducted inside a Class C cargo compartment of a wide-body aircraft. The volume of the compartment was 2000 ± 100 cubic feet (56.6 ± 2.8 $m^3$). Figure 1 illustrates the test article. This compartment was configured to have a leakage rate of 50 ± 5 cubic feet per minute (1.4 ± 0.14 $m^3$ per minute). The original cargo liners were replaced with mild steel sheeting in order to preserve the article for multiple testing; the ceiling was constructed out of 0.0625-inch (1.59-mm) thick sheet, while the sidewalls were made out of 0.050-inch (1.27-mm) thick sheeting. The compartment was equipped with multiple sensors to record temperature, combustion and extinguishing agent gas concentrations, and pressure. On the aft section of the test article, a small camera compartment with a high-temperature glass window was constructed to mount a video camera. A second camera, inside a heat-resistant box, was mounted inside the test bay near the burn area. Lighting was provided by a series of high-wattage lights mounted on the floor and sidewalls of the aircraft compartment.

The cargo compartment ventilation was supplied from the cabin through the floor grills. The cabin was forced ventilated by means of two 10-inch (25.4-cm) -diameter perforated ducts connected to a large fan. The ducts were installed between the cabin ceiling and the overhead storage bins and ran the length of the fuselage. An outflow valve was installed on the aft underside of the fuselage to provide the main outflow for cabin air. This configuration was designed after careful measurements during in-flight tests onboard a B747 and B767 aircraft.

The IHRWG task group members selected a leakage rate of 50 ± 5 CFM (1.4 ± 0.14 CMM) for the standard tests; this selected rate was derived from data provided by Boeing and Airbus. In order to set and verify this leakage rate, a series of carbon dioxide ($CO_2$) depletion tests were performed. Based on the measured $CO_2$ depletion rates, a calculation was made of the actual ventilation leakage rate. Adjustments to the outflow valve and seals in other parts of the fuselage were made to produce the desire leakage rate.

## 2.2 INSTRUMENTATION.

The task group defined the instrumentation requirements; these consisted of thermocouples, gas analyzers, and pressure transducers (see table 1). The output of these sensors were connected to an analog-to-digital converter and collected on a personal computer.

TABLE 1. SENSOR INFORMATION

| Sensor | Model Number | Location | Channel Number |
|---|---|---|---|
| Thermocouple 1 | Thermo Electric Part No. 0129 Type K, 20 Gauge | Ceiling 1 | 22 |
| Thermocouple 2 | Thermo Electric Part No. 0129 Type K, 20 Gauge | Ceiling 2 | 24 |
| Thermocouple 3 | Thermo Electric Part No. 0129 Type K, 20 Gauge | Ceiling 3 | 26 |
| Thermocouple 4 | Thermo Electric Part No. 0129 Type K, 20 Gauge | Sidewall 4 | 34 |
| Thermocouple 5 | Thermo Electric Part No. 0129 Type K, 20 Gauge | Sidewall 5 | 38 |
| Thermocouple 6 | Thermo Electric Part No. 0129 Type K, 20 Gauge | Sidewall 6 | 39 |
| Thermocouple 7 | Thermo Electric Part No. 0129 Type K, 20 Gauge | Ceiling 7 | 27 |
| Thermocouple 8 | Thermo Electric Part No. 0129 Type K, 20 Gauge | Ceiling 8 | 25 |
| Thermocouple 9 | Thermo Electric Part No. 0129 Type K, 20 Gauge | Ceiling 9 | 23 |
| Halon 1 | Rosemount 880A | Centerline and 49″ from the floor, 200″ from the forward wall | 77 |
| Halon 2 | Rosemount 880A | Centerline and 32.5″ from the floor 200″ from the forward wall | 78 |
| Halon 3 | Rosemount 880A | Centerline and 16″ from the floor 200″ from the forward wall | 79 |
| Halon 4 | Rosemount 880A | Near Fire (location changes for each test) | 80 |
| Oxygen 1 | Rosemount OM11EA | Centerline and 49″ from the floor 200″ from the forward wall | 55 |
| Oxygen 2 | Rosemount OM11EA | Centerline and 32.5″ from the floor 200″ from the forward wall | 58 |
| Oxygen 3 | Rosemount OM11EA | Centerline and 16″ from the floor 200″ from the forward wall | 61 |
| Oxygen 4 | Rosemount OM11EA | Near Fire (location changes for each test) | 64 |
| Pressure | Omega PX951-200S5V | Ceiling and 16 3/8″ from Bulk Head, Centerline 208″ from the forward wall | 30 (High-Speed Data Acquisition) |

2.2.1 Temperature Measurement.

A total of 32 thermocouples were available along the ceiling and sidewalls of the compartment and boxes. Only nine thermocouples were reported due to their proximity to the fire. These sensors (Part No. 0129) were type K chromel/alumel 20 gauge thermocouples made by Thermo Electric. The ceiling thermocouples were evenly spaced along the compartment ceiling with a maximum of 5 feet between adjacent thermocouples. One of the ceiling thermocouples was installed directly above the initial ignition location for all fire scenarios. The beads of the ceiling thermocouples, in the fire area, were 1 inch below the compartment ceiling. One of the three sidewall thermocouples was placed 1 foot below the ceiling and centered on the fire ignition location. The sidewall thermocouple was installed on the starboard side of the compartment nearest the ignition location. Two additional thermocouples were placed in and above the box containing the igniter for the bulk and containerized fire scenarios to monitor the progression of the fire.

2.2.2 Halon 1301 and Oxygen Concentration Measurement.

During the execution of the tests, the Halon 1301 and oxygen volumetric concentrations were measured inside the cargo compartment. The compartment had four gas collection probes spaced vertically at different levels from the floor: 16 inches, 32.5 inches, 49 inches, and one that was located near the fire. During the execution of the tests, the Halon 1301 and oxygen volumetric concentrations were measured inside the cargo compartment. The compartment was equipped with four gas collection probes to monitor these volumetric concentrations. The probes were installed in the centerline of the aircraft, 210″ aft of the forward wall and spaced evenly in the vertical axis (compartment height divided into fourths). Probes number 1, 2, and 3 were placed 16.5″, 33″, and 49.5″ above the floor, respectively. The placement of probe number four varied because it depended on the type of fire scenario conducted. During the bulk-load test this fourth probe was located approximately 6″ to the side of the ignition box and 9″ above the floor. When the containerized test was conducted, probe number 4 was placed inside the LD3 container, approximately 6″ from the ignition box and 9″ above the LD3 floor. During the surface burn, it was placed 12″ away from the pan and 12″ below the ceiling. During the aerosol can explosion test, this probe was placed near the igniters which were 36″ in front of the simulator discharge port and 24″ above the floor. These probes were connected to the analyzer by means of a 0.5-inch (12.7-mm) copper tubing network containing particle filters, ice bath, water filters, and pumps.

The measurement of Halon 1301 volumetric concentration in the compartment was carried out using four Rosemount Analytical Model 880A nondispersive infrared absorption analyzers. The analyzers were calibrated against a certified gas mixture, 9.6% by volume of Halon 1301 balanced with nitrogen, before each fire suppression test.

The oxygen volumetric concentration was measured in the compartment by means of four Rosemount Analytical Model OM11EA analyzers. These analyzers used the polarographic oxygen analysis technique to measure the oxygen concentration. The oxygen analyzers used the same sampling lines as the halon analyzers. The sampling probe lines were divided near the analyzers to distribute gas samples to the different analyzers.

2.2.3 Pressure Measurement.

A pressure transducer, Omega model PX951-50S5V, was installed as shown in figure 1 to monitor the overpressure during the aerosol explosion test. This piezoresistive transducer had a pressure range from 0 to 50 psig (0 to 1379 KPa) with a frequency response of 3000 Hz.

2.2.4 Data Collection.

The data collection system was comprised of a 400-channel Philips Workhorse analog-to-digital converter and a 386/33 MHz AT&T Starstation personal computer. Each data channel was programmed in Basic Language to record once every 5 seconds. The pressure data was collected using a data acquisition program from Keithley, model DAS Scan Metrabyte, connected to a Pentium III desktop computer; the Keithley program (data collection software) was setup to sample at a rate of 1000 and 3000 samples per second.

2.3 FIRE LOADS.

The baseline performance of Halon 1301 was determined by exposing it to the four different fire scenarios: bulk-load fire, containerized fire, surface burning, and aerosol can explosion. Each of these fire scenarios had different fire loads simulating potential fire threats in a cargo compartment.

2.3.1 Bulk-Load Fire.

The fire load for this scenario was 178 single-wall corrugated cardboard boxes, with nominal dimensions of 18 × 18 × 18 inches (45.7 × 45.7 × 45.7 cm). A fire load of 30% of the cargo volume was selected by the IHRWG task group as the best compromise between a realistic loading percentage, ensuring enough combustible material for the spread of the fire, minimizing unnecessary set up and clean up efforts, and preventing too high of an initial suppression agent concentration due to the air displaced by the fire load. The weight per unit area of each cardboard box was 0.11 lbs/ft$^2$ (0.54 kg/m$^2$). These boxes were filled with 2.5 pounds (1.13 kg) of shredded office paper, loosely packed without compacting. The weight of each filled box was 4.5 ± 0.4 lbs. (2.05 kg ± 0.18 kg). The flaps of the boxes were tucked under each other with no staples or tape used. The boxes were stacked in two layers inside the cargo compartment without any significant air gaps between them. Ten 1-inch (2.5-cm) -diameter ventilation holes were placed in the side of the initially ignited box to ensure that the fire did not self extinguish (figures 2 and 3).

2.3.2 Containerized Fire.

The same type of cardboard boxes filled with shredded office paper and the same igniter used in the bulk-load fire scenario, section 2.3.1, was used in this scenario. The boxes were stacked inside an LD-3 container as shown in figure 4. The boxes were touching each other with no significant air gaps between them. The container was constructed of an aluminum top and inboard side, a Lexan ™ (polycarbonate) front and the remainder of steel. Two rectangular slots for ventilation were cut into the container in the center of the Lexan™ front and in the center of the sloping sidewall. The slots were 12 by 3 inches ± 1/4 inch (30.5 x 7.6 ± 0.6 cm) (see

figure 5). The igniter was placed in a box on the bottom row, in the corner nearest the sloping side of the container and the Lexan™. Ten, 1.0-inch (2.5-cm) -diameter ventilation holes were placed in the sides of the box. Two additional, empty LD-3 containers were placed adjacent to the first container (see figure 6).

2.3.3 Surface Burning.

For this scenario, the fire load was comprised of 0.5 U.S. gallon (1.9 liters) of Jet A fuel and 13 ounces of gasoline inside a square pan. The pan was constructed of 1/8-inch (0.32-cm) steel and measured 2 feet by 2 feet by 4 inches ($60.9 \times 60.9 \times 10.2$ cm) high. This pan size approximates the size of a small suitcase and the amount of fuel added to it is sufficient to burn for the duration of the test if the extinguishing system is not effective. The gasoline was added to the pan to make ignition easier. In addition to the fuels, 2.5 gallons (9.5 liters) of water was placed at the bottom of the pan to keep the pan cooler and minimize warping. This quantity of fuel and pan size was sufficient to burn vigorously for approximately 4 minutes if not suppressed. The pan was positioned 12 inches (30.5 cm) from the compartment ceiling to provide a difficult location for Halon 1301 to extinguish the fire because halon is approximately five times heavier than air. This pan height also provided fueling accessibility. The pan was located at the maximum horizontal distance from any discharge nozzles (figure 7).

2.3.4 Aerosol Can Explosion.

This scenario addresses the overpressure and bursting of an aerosol can involved in a cargo fire and the potential for the ignition of the released hydrocarbon propellant used in these cans. The FAA William J. Hughes Technical Center developed an aerosol can simulator that releases a mixture of propane and alcohol through a large area valve and across sparking electrodes. [1]

The aerosol explosion simulator utilized a cylindrical pressure vessel for the storage of flammable base product and propellant. The pressure vessel was capable of withstanding a pressure of 300 psi (2068.5 KPa). The pressure vessel was mated to a ball valve capable of withstanding a pressure of 300 psi (2068.5 KPa). The discharge port diameter of the ball valve was 1.5 inches (3.8 cm). The ball valve was capable of rotating from the fully closed position to the fully open position in less than 0.1 second to allow the formation of a vapor cloud. The ball valve was activated by means of pneumatic actuators. The pressure vessel was mounted vertically above the ball valve to allow for complete expulsion of the liquid contents. A discharge elbow located vertically under the ball valve directed the contents horizontally (see figure 8).

The pressure vessel was a steel 2-inch (5.1-cm) diameter, 11-inch (27.9-cm) -long schedule 80 pipe capped at one end. The valve connected to the pressure vessel was a 2-inch DynaQuip® stainless steel valve; this valve was capable of withstanding the interaction between ethanol and propane. A Speedaire® 90-degree pneumatic rotary actuator was used to quickly and reliably rotate the ball valve from closed to fully open. The pressure measurement inside the vessel was accomplished by using a pressure gage fitted to the side of the pipe. The vessel was heated with a hot-air gun, Master Appliance Model HG-501A, to increase the temperature and pressure of the contents; the hot air gun exhaust was directed on the side of the vessel pipe.

The fire load consisted of a base product/propellant mix that weighted 16 ounces (453.6 g). The mix consisted of 20% liquid propane ($C_3H_8$ , 3.2 ounces [90.7 grams]), 60% ethanol (denatured alcohol, 9.6 ounces [272.2 grams]), and 20% water (3.2 ounces [90.7 grams]). These percentages were based on the concentrations found in an actual 16-ounce hair spray aerosol can. This alcohol and water mix was poured in the pressure vessel and then the propane liquid/gas was transferred into the vessel.

## 2.4 IGNITION SOURCE.

Two types of ignition sources were used during the execution of these tests, resistance heat and electrical arc.

### 2.4.1 Resistance.

Applying 115 VAC to a 7-foot length (2.13 m) of nichrome wire ignited the bulk load and containerized fire tests. The wire was wrapped around four folded (in half) paper towels. The resistance of the nichrome igniter coil was approximately 7 ohms. The igniter was placed in the center of the ignited box.

### 2.4.2 Arc.

A set of direct current (DC) arc igniters were used to ignite the fuel in the surface burning tests and the propellant/base product mixture in the aerosol tests. The igniters were connected to a transformer capable of providing 10,000 Volts and 23 mA output. The interchangeable ignition transformer was manufactured by Franceformer®, model number 37.9 (LAHV). The igniters were placed 36 inches (91.4 cm) from the point of discharge for the aerosol simulator test. The igniters were placed about 0.25 inch (6.35 mm) above the surface of the fuel for the surface-burning scenario. The gap in between the two electrodes was 0.25 inch (6.35 mm).

## 2.5 EXTINGUISHING SYSTEM.

The fire extinguishing system used during these tests consisted of two fixed systems and a water spray system with a hand line. One of the fixed systems contained the test agent and the other contained carbon dioxide as a backup.

The Halon 1301/alternative agent suppression system was a balanced system composed of a 945 $in^3$ (0.02 $m^3$) fire bottle, plumbing network with four nozzles on the ceiling of the compartment, and a closed loop metered system. The suppression system was a total flood system designed to initially discharge a specific volumetric concentration in the compartment to quickly knock down the flames and then to maintain the agent's minimum design concentration. The amount of halon used was 38.5 ± 0.1 lbs. (17.5 ± 0.05 kg), super pressurized with nitrogen to 360 psig (2482.2 KPa), which produced a fill density of 70.4 $lbs/ft^3$ (1064.3 $kg/m^3$) in the bottle and an initial 5% volumetric concentration in an empty compartment. The metered system was activated in two of the four fire scenarios, the bulk load and containerized fires. After the initial agent average volumetric concentration dropped to 3.0%, as measured by averaging the reading from the probes at three heights, the metered system was activated to maintain the required minimum design concentration. The closed loop metered system turned on when the volumetric

concentration reached 3%, and it deactivated when it reached 3.2%. The agent was extracted directly from the storage tank using the agent's own vapor pressure as a pump. This system maintained the minimum average concentration required, 3.0%, in order to suppress the fire for the duration of the tests. The halon analyzers output was connected to a data acquisition/controller which monitored the concentration and activated solenoids to add additional agent in order to maintain the minimum design concentration. Note that while an averaging of the Halon concentration measurements was utilized during this test program, such an approach will not meet the latest FAA/JAA compliance harmonization activities which require the use of Halon point concentration measurements. The ignition location and the location of the combustible material is well defined for the fire tests required by this standard. Therefore, the use of an average suppression agent concentration as measured by probes below, above and at the approximate height of the ignition location will give a good indication of the concentration that is actually suppressing the fire.

The following FARs are applicable to cargo compartment fire suppression systems:

FAR 25.851(b)(2). The capacity of each required built-in fire extinguishing system must be adequate for any fire likely to occur in the compartment where used, considering the volume of the compartment and the ventilation rate.

FAR 25.855(h). Flight tests must be conducted to show compliance with the provisions of Sec. 25.857 concerning 25.857(c)(3) for the dissipation of the extinguishing agent in Class C compartments.

Halon 1301 and some of the proposed replacement agents for Halon 1301 are significantly heavier than air and tend to stratify fairly shortly after discharge. The location of a fire in the cargo compartment of an in-service aircraft could be anywhere that cargo is placed. The use of an average agent concentration to show compliance with the above FARs would not be appropriate because it would result in agent concentrations in some parts of the compartment that are below the minimum design concentration that has been shown to be effective.

A second suppression system, a carbon dioxide system, was available in case the tested agent was ineffective. There were two nozzles installed on the sidewalls of the compartment protecting the area. This system was usually used at the end of each test to cool down the compartment and commence the overhaul process.

A 1.5-inch hand line (fire fighter hose), connected to the house water supply, was also available in case the fixed systems failed. It was mainly used at the end of each test to completely extinguish any smoldering combustibles and clean the area.

## 3. TEST PROCEDURES.

### 3.1 BULK-LOAD FIRE GROWTH TESTS.

A fire growth test, in which no suppression agent was used, was conducted in order to provide a baseline for comparison against fire tests utilizing fire-extinguishing agents.

This test scenario was setup by loading 178 cardboard boxes in the compartment as specified in section 2.3.1. The volume of these boxes occupied 30% of the cargo compartment volume. An igniter, (see section 2.4.1) was placed in the center of a box that was located on the bottom outside row of the stacked boxes.

The data acquisition and aircraft ventilation system were activated just before ignition. The nichrome wire igniter was energized and a 30-minute test was conducted. The fire was extinguished with carbon dioxide and water.

### 3.2 BULK-LOAD FIRE SUPPRESSION TESTS.

The procedure used in these tests was the same as the one used in section 3.1 until the activation of the suppression system. The suppression system was activated 1 minute after any of the ceiling thermocouples reached 200°F (93.3°C). When the agent concentration decreased to 3.0%, the metered system was activated to control the smoldering fire until the end of the test. This test scenario was replicated six times and had a test duration of 30 minutes.

### 3.3 CONTAINERIZED FIRE GROWTH TESTS.

A containerized fire growth test was also conducted in order to provide a baseline for this scenario.

In this case, the compartment was loaded with three LD-3 containers as described in section 2.3.2. Thirty-three cardboard boxes were loaded inside one of the containers. An igniter (see section 2.4.1) placed in one of the lower row boxes provided an ignition source.

As in the previous test, the data acquisition system and the aircraft ventilation system were activated just before ignition. The nichrome wire igniter was energized and a 30-minute test was conducted. The fire was extinguished with carbon dioxide and water.

### 3.4 CONTAINERIZED FIRE SUPPRESSION TESTS.

The procedure used in these tests was the same as the one used in section 3.3, until the activation of the suppression system. The suppression system was activated 1 minute after any of the ceiling thermocouples reached 200°F (93.3°C). When the agent concentration decreased to 3.0%, the metered system was activated to control the smoldering fire until the end of the test. This test scenario was replicated five times and each test had duration of 30 minutes after the initial discharge of Halon 1301.

### 3.5 SURFACE-BURNING FIRE GROWTH TESTS.

A 4-$ft^2$ pan, 2 by 2 feet, was placed inside the test compartment (see section 2.3.3) as shown in figure 7. The enclosed box underneath the pan is filled with water and the pan is filled with 13 ounces (0.37 kg) of gasoline and 0.5 U.S. gallon (1.9 liters) of Jet A fuel. The pan was located 12 inches (30.5 cm) below the cargo compartment ceiling. After initiating the cargo compartment leakage ventilation and starting the data acquisition system, the fuel was ignited by using the spark igniter detailed in section 2.4.2. The fire was allowed to burn until all the fuel

was consumed. The test lasted 6 minutes. The data collected provided the baseline for this scenario.

## 3.6 SURFACE-BURNING FIRE SUPPRESSION TESTS.

This test used the same procedure as in section 3.5 until the halon discharge. As in the other test scenarios, the halon was discharged 1 minute after any of the ceiling thermocouples reached 200°F (93.3°C). This test was allowed to run for 5 additional minutes.

## 3.7 AEROSOL CAN EXPLOSION TESTS.

Aerosol can explosion tests were not conducted in the DC-10 compartment in order to preserve the structural integrity of the test article. Instead, they were performed in a pressure vessel capable of withstanding a 1000 psig (6895 KPa) overpressure. Here, the simulator was assembled and filled as described in section 2.3.4. Its discharge port and the spark igniter were mounted 2 feet (0.61 m) above the compartment floor. The spark igniter was 36 inches (0.91 m) away from the discharge port. The test was initiated by heating the pressure vessel to raise the pressure of the contents to 210 ± 5 psi (1448 KPa). At that pressure, the spark igniters were turned on and the simulator was activated to release its flammable/explosive mixture. High-speed data collection, at a rate of 1000 samples per second, was started just before releasing the explosive mixture.

## 3.8 AEROSOL CAN EXPLOSION INERTING TESTS.

These tests were conducted in the DC-10 cargo compartment using the same procedures described in section 3.7. After filling up and mounting the simulator on its stand, the compartment doors were closed and the 50 CFM (1.4 CMM) leakage ventilation system was initiated. The 3000 Hz data collection system and the video recorders were then started. The simulator was heated until the contents reached a pressure of 210 psi (1448 Kpa), and then Halon 1301 was discharged into the compartment. The Halon concentration at the height of the simulator discharge opening was monitored until it had decayed to the minimum design concentration of 3.0%. The arcing electrodes were then energized. The high-speed data collection system was activated, and then the contents of the simulator were released. The test ended 10 seconds after the release of the simulator contents.

# 4. RESULTS.

The test results for the four fire scenarios, with and without suppression, are described in the next subsections. Table 2 provides a general description of the tests, table 3 summarizes the test results, and table 4 presents statistical information about the results. Time boundaries were established for the determination of the peak temperatures and the calculation of the area under the time-temperature curve in order to set a reference frame (see figure 9). These boundaries provided the necessary time for the agent to react and combat the fire. The time boundaries established for the determination of the recorded maximum temperature started 1 minute 30 seconds after a cargo compartment thermocouple reached 200°F (93.3°C) and ended 29 minutes 30 seconds later. The boundaries to calculate the area under the time-temperature curve started 1

TABLE 2. GENERAL TEST INFORMATION

| Test Number | Fire Test Scenario | Test ID | Suppression System | Comments |
|---|---|---|---|---|
| 1 | Bulk Load | 091594T1 | No Extinguishing Agent | |
| 2 | Bulk Load | 081198T1 | 38.5 lbs. of Halon 1301 | -Metered System Activated<br>-Cabin forward door was found opened after test |
| 3 | Bulk Load | 081298T1 | 38.5 lbs. of Halon 1301 | Metered System Activated |
| 4 | Bulk Load | 081398T2 | 38.5 lbs. of Halon 1301 | Metered System Activated |
| 5 | Bulk Load | 081498T1 | 38.5 lbs. of Halon 1301 | Metered System Activated |
| 6 | Bulk Load | 081998T1 | 38.5 lbs. of Halon 1301 | Metered System Activated |
| 7 | Bulk Load | 082198T3 | 38.5 lbs. of Halon 1301 | Metered System Activated |
| 8 | Containerized | 082898T1 | 38.5 lbs. of Halon 1301 | Metered System Activated |
| 9 | Containerized | 083198T1 | 38.5 lbs. of Halon 1301 | Metered System Activated |
| 10 | Containerized | 090298T1 | 38.5 lbs. of Halon 1301 | Metered System Activated |
| 11 | Containerized | 090498T1 | 38.5 lbs. of Halon 1301 | Metered System Activated |
| 12 | Containerized | 091998T1 | 38.5 lbs. of Halon 1301 | Metered System Activated |
| 13 | Containerized | 110998T1 | No Extinguishing Agent | |
| 14 | Surface Burn | 111899T3 | 38.6 lbs. of Halon 1301 | |
| 15 | Surface Burn | 111899T4 | 38.6 lbs. of Halon 1301 | |
| 16 | Surface Burn | 111999T1 | 38.6 lbs. of Halon 1301 | |
| 17 | Surface Burn | 111999T2 | 37.0 lbs. of Halon 1301 | |
| 18 | Surface Burn | 111999T3 | 38.6 lbs. of Halon 1301 | |
| 19 | Surface Burn | 111999T4 | No Extinguishing Agent | |
| 20 | Aerosol Explosion | 022599T6 | No Extinguishing Agent | Tested in pressure vessel |
| 21 | Aerosol Explosion | 022599T7 | No Extinguishing Agent | Tested in pressure vessel |
| 22 | Aerosol Explosion | 022599T8 | No Extinguishing Agent | Tested in pressure vessel |
| 23 | Aerosol Explosion | 022599T9 | No Extinguishing Agent | Tested in pressure vessel |
| 24 | Aerosol Explosion | 022599T11 | No Extinguishing Agent | Tested in pressure vessel |
| 25 | Aerosol Explosion | 122199T1 | 38.6 lbs. of Halon 1301 | |
| 26 | Aerosol Explosion | 122199T3 | 38.6 lbs. of Halon 1301 | |
| 27 | Aerosol Explosion | 122299T1 | 38.6 lbs. of Halon 1301 | |
| 28 | Aerosol Explosion | 122299T2 | 38.6 lbs. of Halon 1301 | |
| 29 | Aerosol Explosion | 122299T3 | 38.6 lbs. of Halon 1301 | |

minute after a cargo compartment thermocouple reached 200°F (93.3°C) and ended 30 minutes later. These calculations and determinations were performed on the data of all of the thermocouples but only the maximum values were tabulated. Also, sensors that experience significant activity were plotted.

## TABLE 3. TEST RESULTS

| Test Number | Fire Test Scenario | Test ID | Maximum Ceiling Temperature* | Maximum Sidewall Temperature | Oxygen at Maximum Ceiling Temp | Avg Halon at Maximum Ceiling Temp | Maximum Area Time-Temperature | Maximum Pressure | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Bulk Load | 091594T1 | 1233°F (667°C) | 1088°F (587°C) | 18.6% | 0.0% | 17404°F-min (9651°C-min) | N/A | No agent used, see figures 10 & 17 |
| 2 | Bulk Load | 081198T1 | 511°F (266°C) | 230°F (110°C) | 17.4% | 6.0% | 8646°F-min (4785°C-min) | N/A | 5% Halon 1301*, see figures 11, 18, & 24 |
| 3 | Bulk Load | 081298T1 | 431°F (222°C) | 276°F (136°C) | 10.5% | 2.8% | 9511°F-min (5266°C-min) | N/A | 5% Halon 1301*, see figures 12, 19, & 25 |
| 4 | Bulk Load | 081398T2 | 450°F (232°C) | 267°F (130°C) | 16.0% | 5.5% | 9953°F-min (5512°C-min) | N/A | 5% Halon 1301*, see figures, 13, 20, & 26 |
| 5 | Bulk Load | 081498T1 | 410°F (210°C) | 269°F (132°C) | 18.0% | 5.9% | 9928°F-min (5498°C-min) | N/A | 5% Halon 1301*, see figures 14, 21, & 27 |
| 6 | Bulk Load | 081998T1 | 665°F (352°C) | 286°F (141°C) | 15.0% | 5.5% | 10839°F-min (6004°C-min) | N/A | 5% Halon 1301*, see figures 15, 22, & 28 |
| 7 | Bulk Load | 082198T3 | 470°F (243°C) | 250°F (121°C) | 16.5% | 6.6% | 9518°F-min (5270°C-min) | N/A | 5% Halon 1301*, see figures 16, 23, & 29 |
| 8 | Containerized | 082898T1 | 607°F (320°C) | 265°F (129°C) | 13.6% | 3.7% | 14011°F-min (7766°C-min) | N/A | 5% Halon 1301*, see figures 30, 36, & 42 |
| 9 | Containerized | 083198T1 | 577°F (303°C) | 287°F (141°C) | 12.9% | 3.5% | 13565°F-min (7518°C-min) | N/A | 5% Halon 1301* see figures 31, 37, & 43 |
| 10 | Containerized | 090198T1 | 606°F (319°C) | 243°F (117°C) | 10.9% | 3.2% | 13793°F-min (7645°C-min) | N/A | 5% Halon 1301* see figures 32, 38, & 44 |
| 11 | Containerized | 090298T1 | 520°F (271°C) | 282°F (139°C) | 12.4% | 3.6% | 12680°F-min (7027°C-min) | N/A | 5% Halon 1301* see figures 33, 39, & 45 |
| 12 | Containerized | 090498T1 | 498°F (259°C) | 280°F (138°C) | 11.7% | 3.2% | 11717°F-min (6492°C-min) | N/A | 5% Halon 1301*, see figures 34, 40, & 46 |
| 13 | Containerized | 110998T1 | 813°F (434°C) | 384°F (196°C) | 8.2% | 0.0% | 21694°F-min (12035°C-min) | N/A | No agent used, see figures 35 & 41 |
| 14 | Surface Burn | 111899T3 | 1138°F (614°C) | 106°F (41°C) | 18.8% | 3.0% | 2952°F-min (1622°C-min) | N/A | 5% Halon 1301*, see figures 47, 53, & 59 |
| 15 | Surface Burn | 111899T4 | 1051°F (566°C) | 117°F (47°C) | 19.0% | 3.1% | 2900°F-min (1593°C-min) | N/A | 5% Halon 1301*, see figures 48, 54, & 60 |
| 16 | Surface Burn | 111999T1 | 1111°F (600°C) | 115°F (46°C) | - | 3.8% | 2973°F-min (1634°C-min) | N/A | 5% Halon 1301*, see figures 49, 55, & 61 |
| 17 | Surface Burn | 111999T2 | 1038°F (559°C) | 115°F (46°C) | 19.0% | 4.3% | 2817°F-min (1547°C-min) | N/A | 5% Halon 1301*, see figures 50, 56, & 62 |
| 18 | Surface Burn | 111999T3 | 1078°F (581°C) | 119°F (48°C) | 18.8% | 5.0% | 2835°F-min (1557°C-min) | N/A | 5% Halon 1301*, see figures 51, 57, & 63 |
| 19 | Surface Burn | 111999T4 | 1340°F (727°C) | 221°F (105°C) | 21.0% | 0.0% | 5822°F-min (3217°C-min) | N/A | No agent used, see figures 52 & 58 |
| 20 | Aerosol Explosion | 022599T6 | - | - | 21.0% | 0.0% | N/A | 30.1 psig (207.9 kPa) | No agent used, see figure 79 |
| 21 | Aerosol Explosion | 022599T7 | - | - | 21.0% | 0.0% | N/A | 32.2 psig (221.9 kPa) | No agent used, see figure 80 |
| 22 | Aerosol Explosion | 022599T8 | - | - | 21.0% | 0.0% | N/A | 32.1 psig (221.2 kPa) | No agent used, see figure 81 |
| 23 | Aerosol Explosion | 022599T9 | - | - | 21.0% | 0.0% | N/A | 31.2 psig (215.5 kPa) | No agent used, see figure 82 |
| 24 | Aerosol Explosion | 022599T10 | - | - | 21.0% | 0.0% | N/A | 28.2 psig (195.0 kPa) | No agent used, see figure 83 |
| 25 | Aerosol Explosion | 122199T1 | 60°F (16°C) | 52°F (11°C) | 21.0% | 0.0% | N/A | 0.0 psig (0.0 kPa) | 5% Halon 1301*, see figures 64, 69, & 74 |
| 26 | Aerosol Explosion | 122199T3 | 57°F (14°C) | 49°F (9°C) | 21.0% | 0.0% | N/A | 0.0 psig (0.0 kPa) | 5% Halon 1301*, see figures 65, 70, & 75 |
| 27 | Aerosol Explosion | 122299T1 | 57°F (14°C) | 49°F (9°C) | 21.0% | 0.0% | N/A | 0.0 psig (0.0 kPa) | 5% Halon 1301*, see figures 66, 71, & 76 |
| 28 | Aerosol Explosion | 122299T2 | 58°F (14°C) | 48°F (9°C) | 21.0% | 0.0% | N/A | 0.0 psig (0.0 kPa) | 5% Halon 1301*, flash occurred, see figures 67, 72, & 77 |
| 29 | Aerosol Explosion | 122299T3 | 50°F (10°C) | 43°F (6°C) | 21.0% | 0.0% | N/A | 0.0 psig (0.0 kPa) | 5% Halon 1301*, see figures 68, 73, & 78 |

* 5% Volumetric concentration is based on a 2000 $ft^3$ empty compartment

TABLE 4. RESULTS STATISTICS

| Function | Bulk-Load Peak Temp (°F) | Bulk-Load Area | Containerized Peak Temp (°F) | Containerized Area | Surface Burn Peak Temp (°F) | Surface Burn Area | Aerosol Explosion (psig) |
|---|---|---|---|---|---|---|---|
| Maximum | 665 | 10839 | 607 | 14011 | 1138 | 2973 | 0 |
| Minimum | 410 | 8646 | 498 | 11717 | 1038 | 2817 | 0 |
| Average | 490 | 9733 | 562 | 13153 | 1083 | 2895 | 0 |
| Standard Deviation | 84.6 | 657 | 45 | 849 | 37 | 62 | 0 |
| Maximum + 10% | 731.5 | 11923 | 668 | 15412 | 1252 | 3270 | 0 |
| MPS Acceptance Criteria | 730 | 11900 | 670 | 15400 | 1250 | 3270 | 0 |

The charts were organized first by test scenario and second by sensor type; for example, figures 10 through 16 are temperature data that was collected during a bulk-load test. Therefore, the figure numbers will not be called in sequence.

## 4.1 BULK-LOAD FIRE GROWTH TEST.

Test 1 was a baseline bulk-load fire test that was conducted for 30 minutes. No extinguishing agent was discharged in the compartment during that period. Figure 10 shows a plot of the temperature history recorded by two thermocouples and figure 17 shows the oxygen concentration at the ceiling. These charts indicate that a flashover occurred inside the cargo compartment. Flashover refers to a situation where a fire in an enclosure changes from a relatively localized area of combustion to a fire involving almost all the combustible material in the enclosure due to the ignition of combustible gases in the smoke layer. As shown in figure 17 the flashover caused a large reduction in oxygen which did not change for the remainder of the test. A maximum temperature of 1233°F (667°C) was recorded on the cargo compartment ceiling by thermocouple number 2. Thermocouple number 5 recorded the peak temperature, 1088°F (587°C), found on the compartment sidewalls. The oxygen concentration at the ceiling level was 18.6% when the ceiling temperature was at its peak. The area under the time-temperature curve was calculated over a duration of 30 minutes after discharge. This computation resulted in an area of 17404°F-min (9628°C-min). Five minutes after reaching its maximum temperature peak, the temperatures on the ceiling and sidewalls descended to between 400°F and 600°F. The oxygen concentrations at this time ranged between 5% and 7% (figure 17), which was not sufficient for flaming combustion.

## 4.2 BULK-LOAD FIRE SUPPRESSION TESTS.

Tests 2 through 7 were fire suppression tests employing Halon 1301 against the bulk-load fire scenario. As expected, none of these fires were completely extinguished with Halon 1301, but they were effectively suppressed. An initial peak of 6% to 7% volumetric concentration was measured in the compartment due to a 30% reduction in empty space created by the addition of the cardboard boxes. This initial concentration extinguished any open flames which prevented a flashover condition. The secondary closed loop metered system was activated when the halon concentration decayed to 3%. This prevented flaming combustion and protected the cargo

compartment for the duration of the test. Figures 11 through 16 show the temperature history of the ceiling and sidewall of the forward compartment (fire area). As seen in table 3, the maximum ceiling temperatures ranged from 410°F (210°C) to 665°F (352°C) after the agent was discharged. This was a significant drop in temperature when compared to the maximum value obtained when no agent was used, 1233°F (667°C). The sidewalls temperatures were even lower during the 30-minute tests, with maximums ranging from 230°F (110°C) to 286°F (141°C). The oxygen and Halon 1301 (volumetric) concentrations, at these peak temperatures, were between 10.5% and 18%, and 2.8% and 6.6%, respectively (see figures 18 through 23). The maximum area under the time-temperature curve was calculated for each of the tests conducted. The result shows that the calculated areas were smaller, i.e., cooler temperatures than obtained during the uncontrolled fire test; the calculated values ranged from 8646°F-min (4785°C-min) to 10839°F-min (6004°C-min). Figures 24 through 29 are superimposed plots of the temperature and halon volumetric concentration histories in order to illustrate the effects of the extinguishing agent on the temperature as it was discharged and expanded in the compartment.

## 4.3 CONTAINERIZED FIRE GROWTH TEST.

Test 13, a containerized fire growth test, was conducted for 30 minutes and no extinguishing agent was discharged in the compartment. Figures 35 and 41 show plots of the temperature histories of nine thermocouples (ceiling and sidewall) and oxygen concentrations at four different levels respectively. A peak temperature of 813°F (434°C) was recorded at the cargo compartment ceiling, while the peak sidewall temperature was only 384°F (196°C). The oxygen reading of the probe inside the LD3 container suggests that a flashover occurred during this test. As seen in figure 41, oxygen probe #4 dropped quickly below 1% 5 minutes after ignition. Because there is oxygen in the cargo compartment, the oxygen rises in the LD3 container and decreases in the cargo compartment (oxygen flows from compartment to container). The increase in oxygen in the container allows burning inside the container, resulting in high compartment temperature readings. The oxygen concentration at the ceiling level was 8.2% when the ceiling temperature was at its peak. The area under the time-temperature curve was calculated and resulted in an area of 21633°F-min (12001°C-min). The uncontrolled container fire caused high compartment temperatures; even though this test scenario did not record the highest peak temperature, it had the largest area under the time-temperature curve. For example, ceiling temperatures above the container were about 700°F to 800°F (371.1°C to 426.7°C) for more than 20 minutes. The compartment oxygen concentrations over this time decreased from about 15% to 7% (figure 41).

## 4.4 CONTAINERIZED FIRE SUPPRESSION TESTS.

Tests 8 through 12 were fire suppression tests discharging Halon 1301 in the containerized fire scenario. Once again, as expected, the halon did not extinguish these deep-seated fires, but effectively suppressed them. The initial 5% to 7% volumetric concentration of this gas completely flooded the cargo compartment and extinguished the flaming combustion. The secondary suppression system was activated when the average halon concentration decayed to 3%. Figures 30 through 34 illustrate the ceiling temperature histories where maximum values ranged from 498°F (259°C) to 607°F (320°C) after the agent was discharged. The peak temperature difference between a controlled and uncontrolled fire in a compartment was not as

dramatic as in the case of the bulk-load scenario, but cooler temperatures and suppression were achieved. It appears to have been more difficult for the halon to penetrate into the container and control the combustion process even though the polycarbonate panel on the LD3 container melted and burned. The sidewalls experienced temperatures ranging from 243°F (117°C) to 287°F (141°C), which were comparable to the bulk-load fire data. Gas probe number 4 was placed inside the LD3 container to monitor the different gas concentrations during the combustion process. The oxygen and Halon 1301 (volumetric) concentration levels were between 10.9% and 13.6%, and 3.2% and 3.7%, respectively, when the maximum ceiling temperature occurred (figures 36 through 40). The calculated area under the time-temperature curve ranged from 12680°F-min (7027°C-min) to 14011°F-min (7766°C-min). These calculated values were smaller than during the uncontrolled fire test but were higher than the bulk-load fire suppressed scenario. The effects of the agent on the temperatures can be seen in figures 42 through 46.

## 4.5 SURFACE-BURNING FIRE GROWTH TEST.

Test 19 was a baseline test for the surface-burning fire scenario without extinguishing agent. Figure 52 illustrates the temperature history of the burning fuel. The maximum temperature reached on the ceiling was 1340°F (727°C) and on the sidewall 221°F (105°C). The fuel was consumed in about 4 to 5 minutes, and the oxygen level remained above 16.5% during this interval (figure 58). As expected, this test generated the highest peak temperatures of all of the different test scenarios. The area under the curve was calculated using a narrower boundary. The boundary was delineated to be from 1 minute after any of the thermocouples on the ceiling reached 200°F (93.3°C) to the end of the test, 5 minutes later. The calculated area under the time-temperature curve was 5822°F-min (3217°C-min).

## 4.6 SURFACE-BURNING FIRE SUPPRESSION TESTS.

Tests 14 through 18 were the surface-burning fire suppression tests. The temperature histories may be viewed in figures 47 through 51. During these tests, the fires were completely extinguished within 1 minute so the metered system was not required. Also, the tests were very repeatable as demonstrated by the temperature profiles. The ceiling instrumentation recorded peak temperatures that ranged from 1038°F (559°C) to 1138°F (614°C) and sidewall temperatures ranging from 106°F (41°C) to 119°F (48°C). The oxygen level did not drop lower than 18.8%, which was sufficient for a fuel fire to continue burning if the extinguishing agent was not effective (figures 53 through 57). The concentration levels of Halon 1301, at the time the temperature reached its peak, ranged from 3% to 5%; these levels were sufficient to extinguish the fire (refer to figures 59 through 63). Using the same time boundaries as in the uncontrolled case, the computed area under the time-temperature curve ranged from 2817°F-min (1547°C-min) to 2973°F-min (1634°C-min).

## 4.7 AEROSOL CAN EXPLOSION TESTS.

As shown in table 2, tests 20 through 24 are identified as the aerosol can fire explosion tests. These tests were not conducted inside the DC-10 cargo compartment in order to preserve the structural integrity of the test article. Instead, they were performed in a 353-$ft^3$ (10 $m^3$) pressure

vessel that was capable of withstanding 1000 psig (6895 KPa) and had a working pressure rating of 600 psig (4137 KPa). The only instrumentation available in this vessel was a single pressure transducer. The peak pressures recorded during the explosions ranged from 28.2 psig to 32.2 psig (see figures 79 through 83). Video and high-speed film footage were taken to record the event. The footage includes the pre- and postignition events such as content discharge and the large fireballs (deflagrations) that were created after the contents of the simulator ignited.

### 4.8 AEROSOL CAN EXPLOSION INERTING TESTS.

The last test series, tests 25 through 29, were conducted to determine the inerting capabilities of Halon 1301 under the described test conditions. This series of tests was conducted in the DC-10 under the same conditions as in previous tests. Seconds after the volumetric concentration of halon decayed to 3%, the contents of the aerosol simulator were discharged and exposed to a set of arcing electrodes. No explosions occurred. There was no ignition of the contents of the simulator in four of the five tests. There was a very brief ignition of some of the contents during one test (test 28), but no overpressure was recorded. There was no increase in pressure within the compartment during the 10 seconds from the discharge of the simulator until the end of the test. The data acquisition system was collecting at a rate of 3000 samples per second. There was no temperature increase in the compartment after the simulator was opened (figures 64 through 68). The temperature fluctuations seen in the graphs were due to the discharge of halon in the compartment (figures 74 through 78). There was some temperature difference between the installed thermocouples, but it was due to their proximity to light fixtures. The oxygen level dropped 1% to 2% from its original level of 21%, due to the introduction of halon. The gas concentration history in the compartment can be seen in figures 69 through 73.

## 5. SUMMARY OF FINDINGS.

The fire suppression performance of Halon 1301 was characterized in this program for four different fire scenarios: bulk-load fires (Class A fire), containerized fires (Class A fire), surface burn (Class B fire), and aerosol can explosions. The characterizations are the basis for the fire performance of halon replacement agents contained in a minimum performance standard (appendix A). It was determined that

- Halon 1301 was capable of extinguishing open flames and suppressing fire growth during the bulk-load Class A and containerized deep-seated Class A fires.
- Surface burn Class B fires (Jet A fuel in a pan) were completely extinguished with Halon 1301 in less than 1 minute.
- A volumetric concentration of 3% Halon 1301 prevented the explosion of an explosive hydrocarbon mixture, simulating the failure of an aerosol can, released in the cargo compartment and exposed to an ignition source.

## 6. REFERENCE.

1. T. Marker, "Initial Development of an Exploding Aerosol Can Simulator," DOT/FAA/AR-TN97/103, 1998.

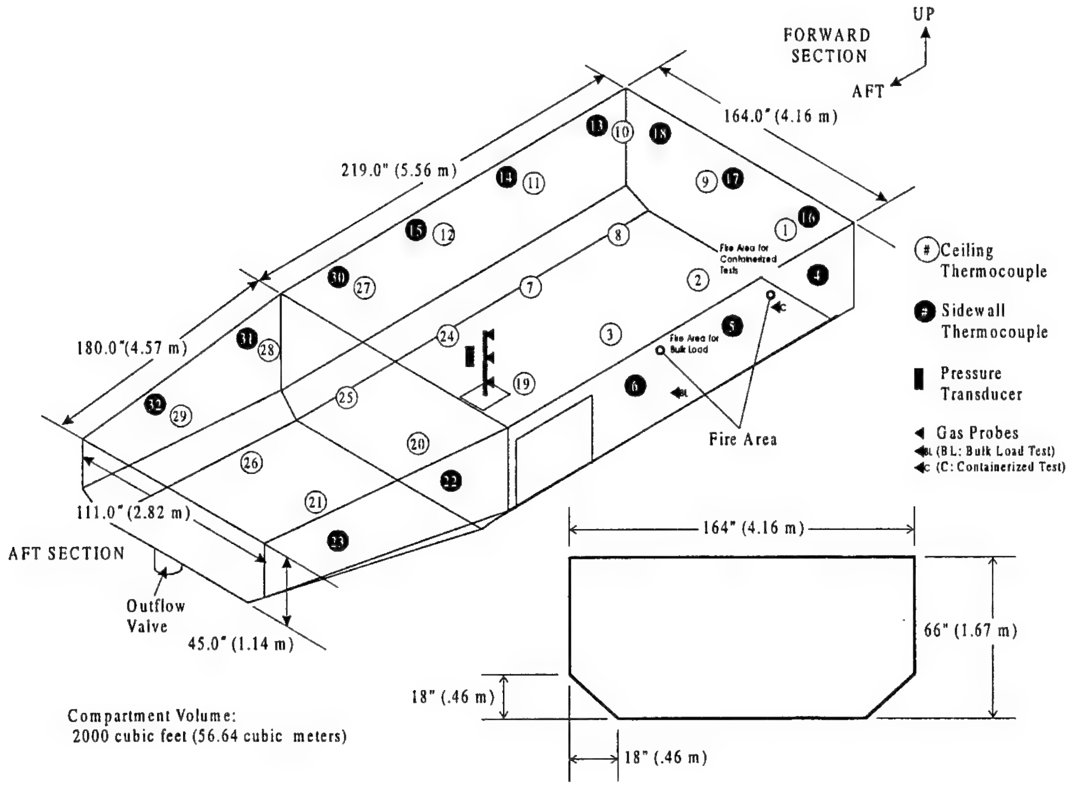


FIGURE 1. CARGO COMPARTMENT LAYOUT AND INSTRUMENTATION LOCATIONS

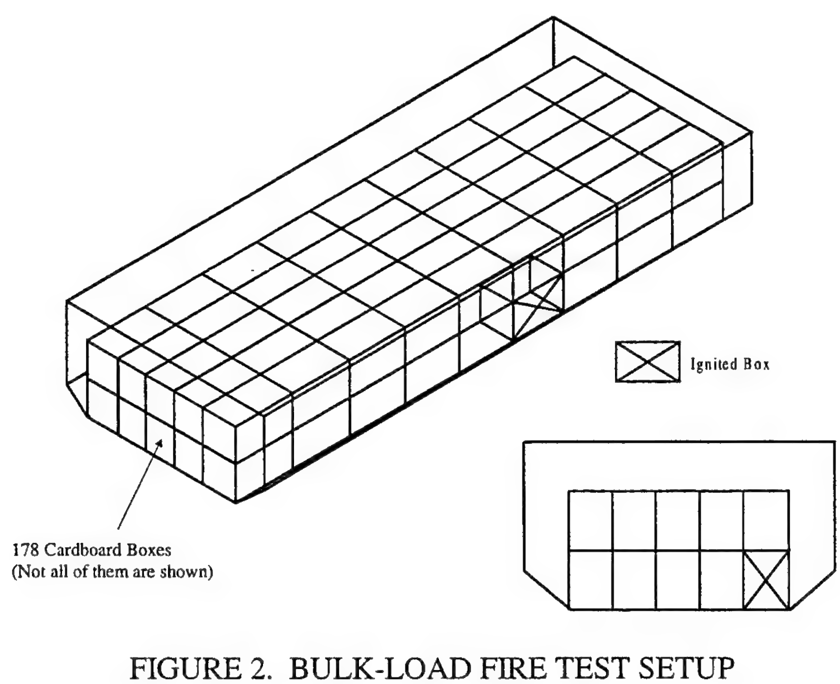


FIGURE 2. BULK-LOAD FIRE TEST SETUP

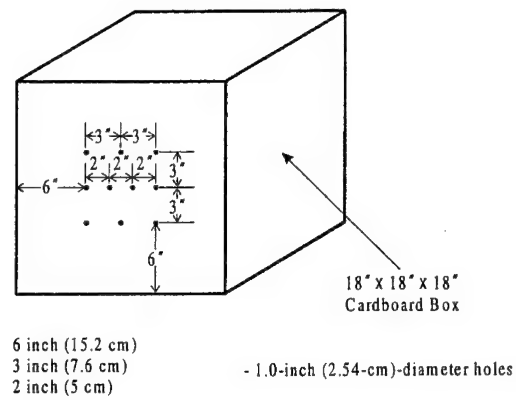


FIGURE 3. IGNITER BOX

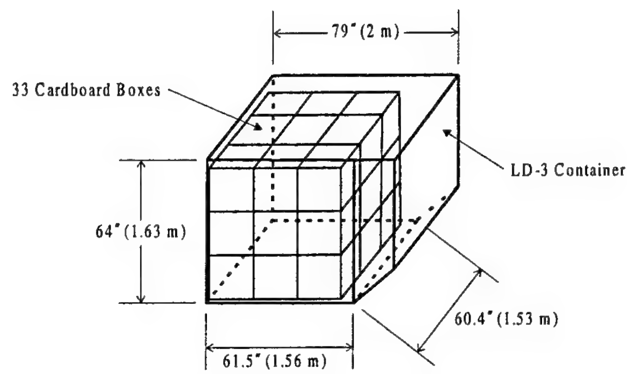


FIGURE 4. CONTAINERIZED FIRE TEST SETUP

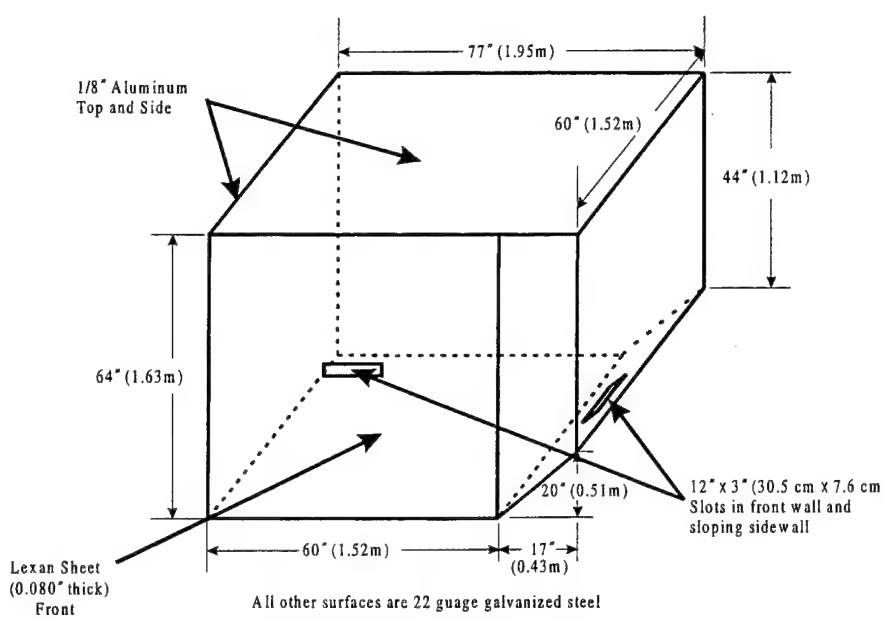


FIGURE 5. LD-3 CONTAINER

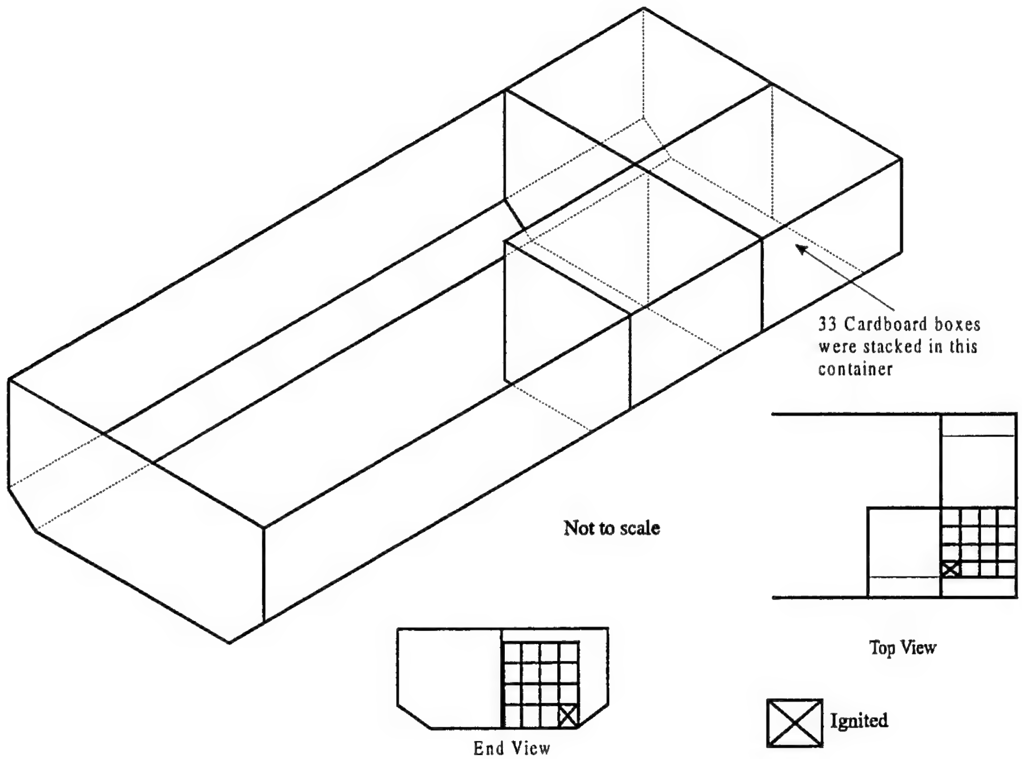


FIGURE 6. LD-3 CONTAINERS ARRANGEMENT

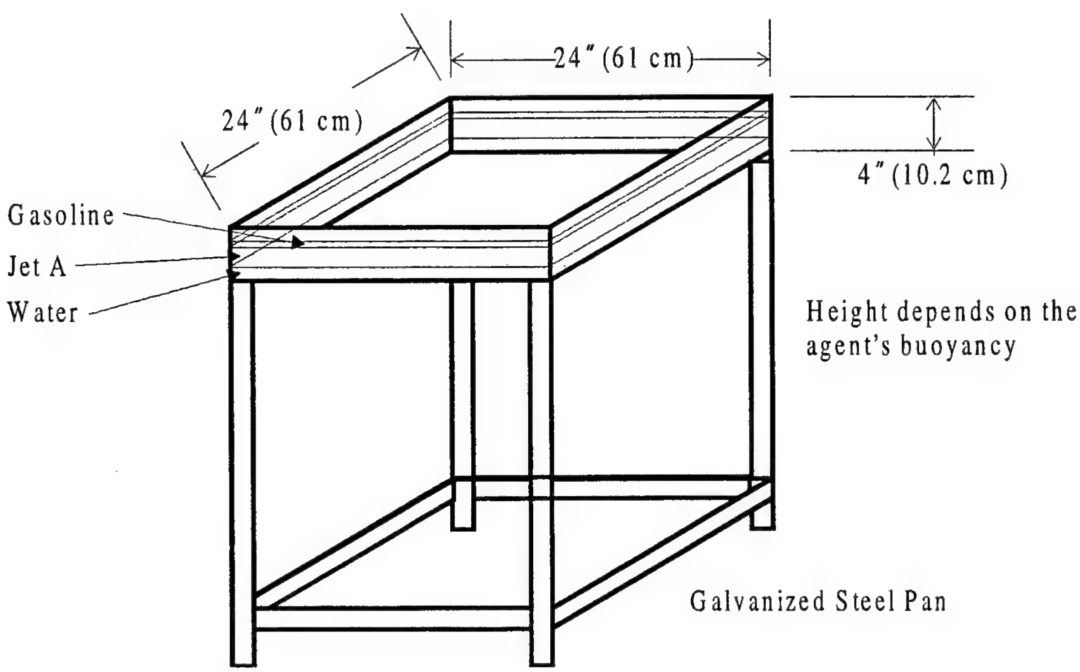


FIGURE 7. SURFACE BURNING FIRE PAN

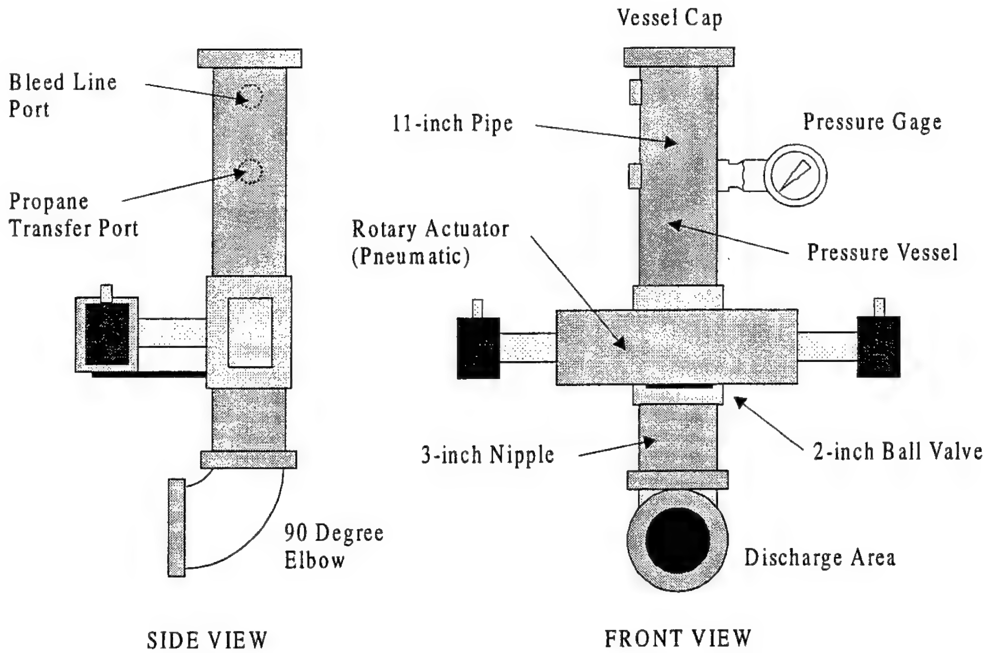


FIGURE 8. SCHEMATIC OF AEROSOL EXPLOSION SIMULATOR

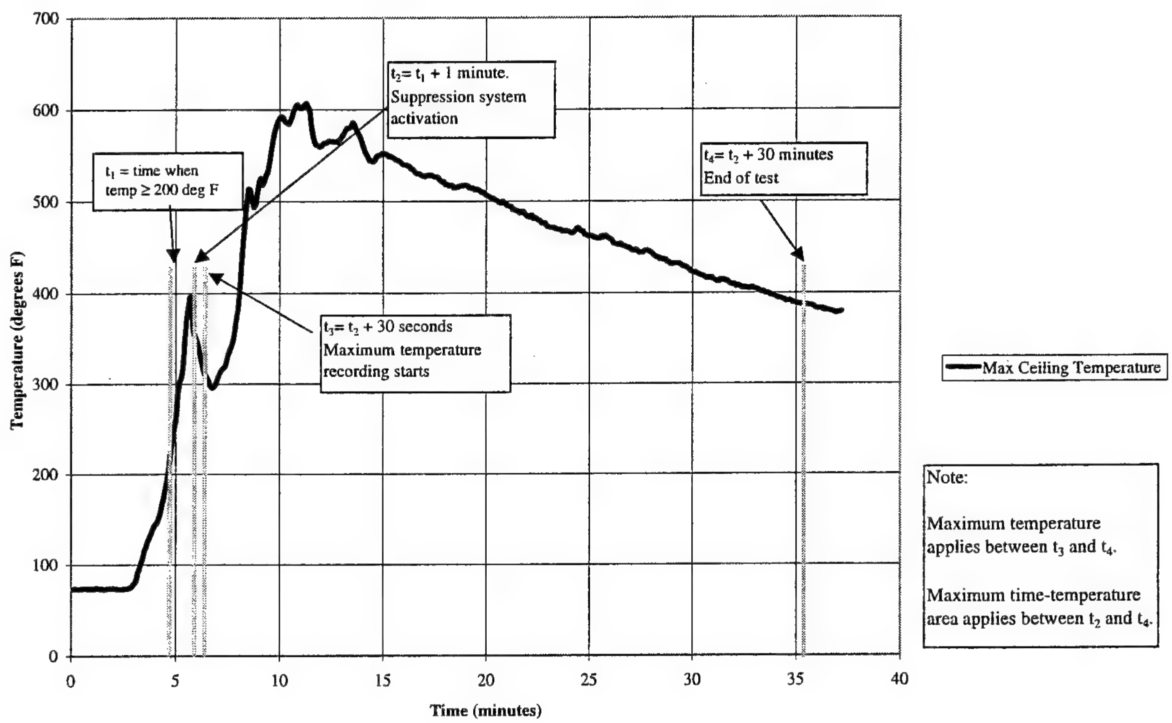


FIGURE 9. ACCEPTANCE CRITERIA BOUNDARIES

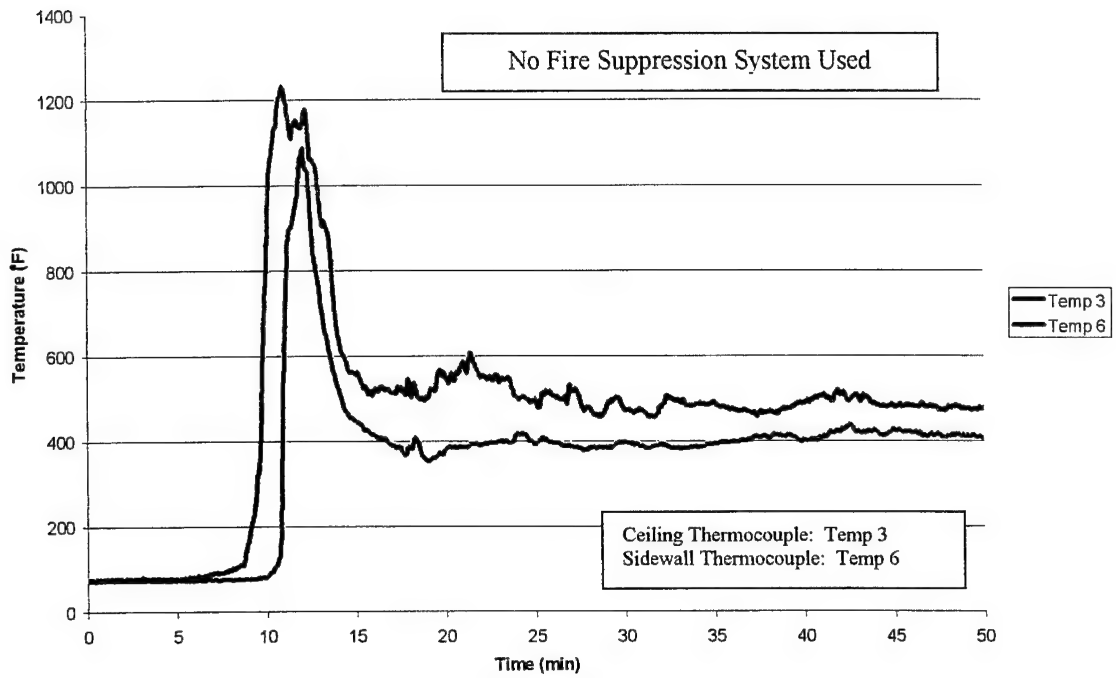


FIGURE 10. BULK-LOAD TEST 1 (091594T1) TEMPERATURE PLOT

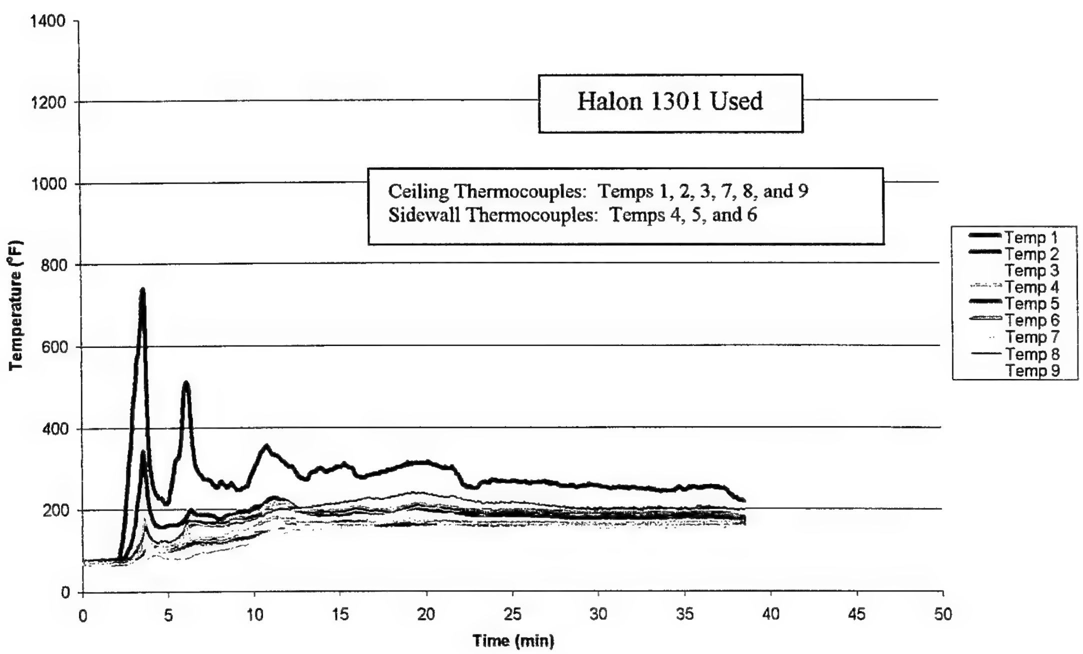


FIGURE 11. BULK-LOAD TEST 2 (081198T1) TEMPERATURE PLOT

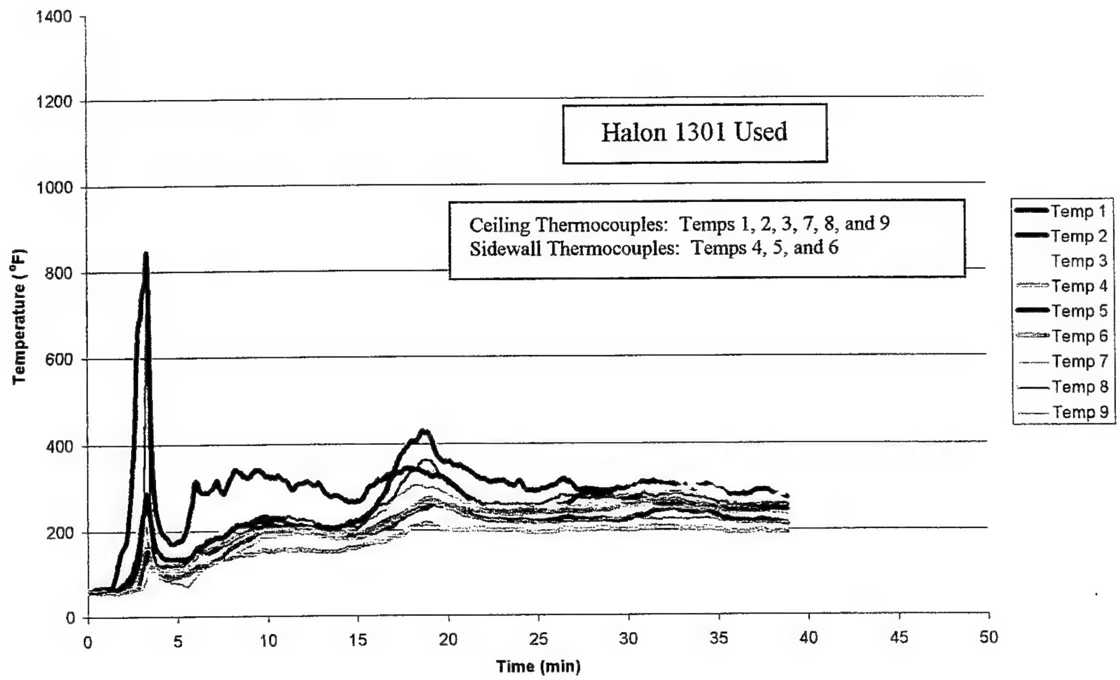


FIGURE 12. BULK-LOAD TEST 3 (081298T1) TEMPERATURE PLOT

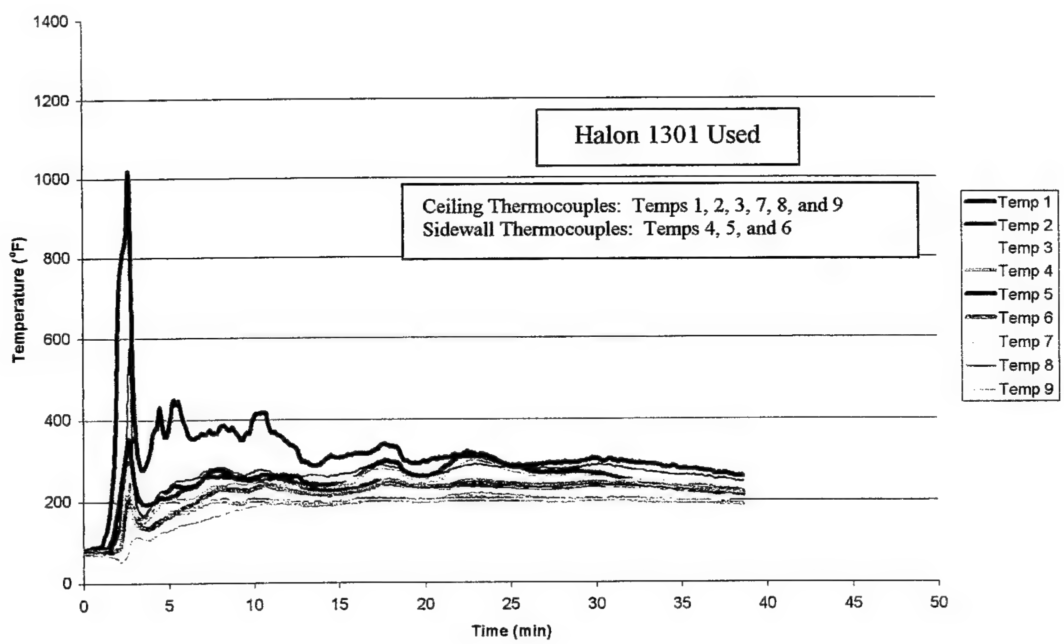


FIGURE 13. BULK-LOAD TEST 4 (081398T2) TEMPERATURE PLOT

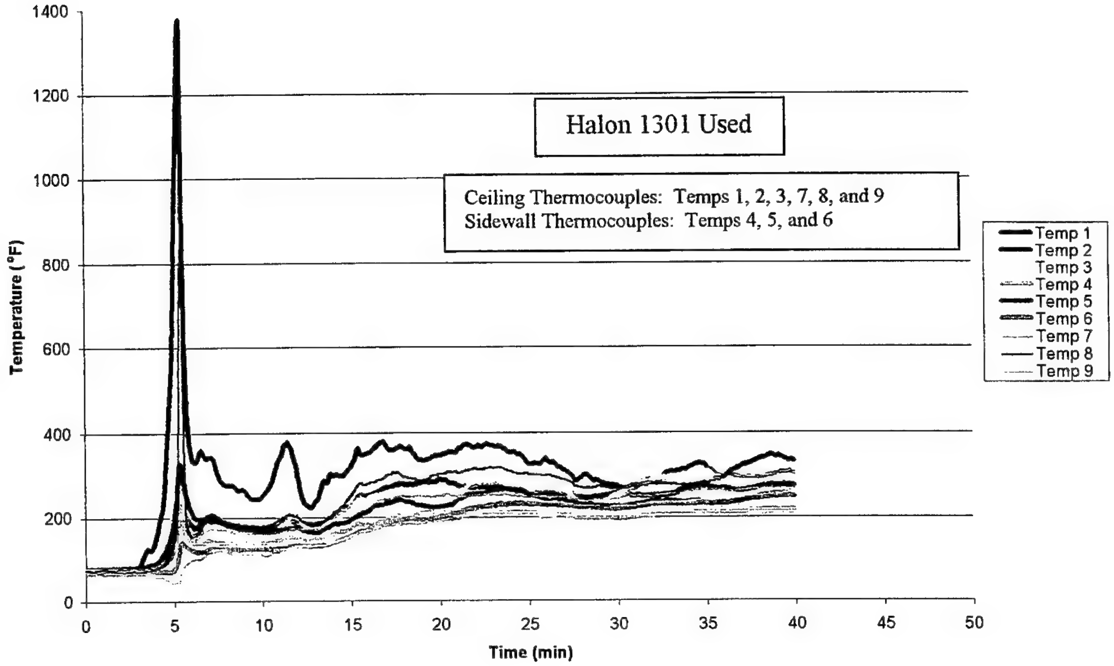


FIGURE 14. BULK-LOAD TEST 5 (081498T1) TEMPERATURE PLOT

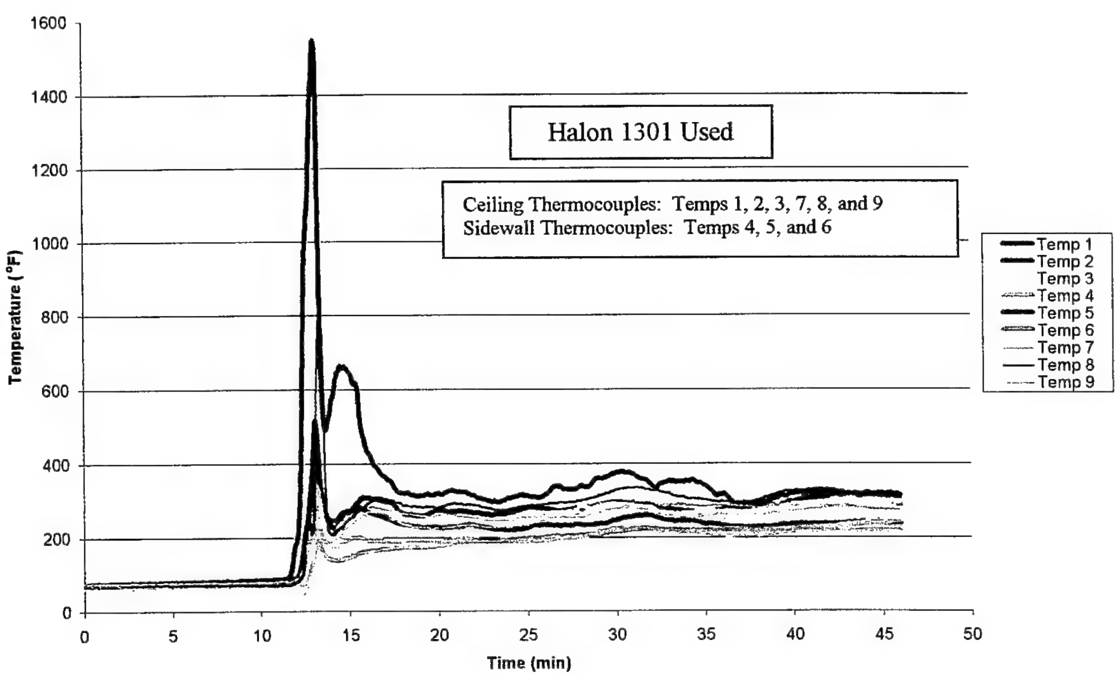


FIGURE 15. BULK-LOAD TEST 6 (081998T1) TEMPERATURE PLOT

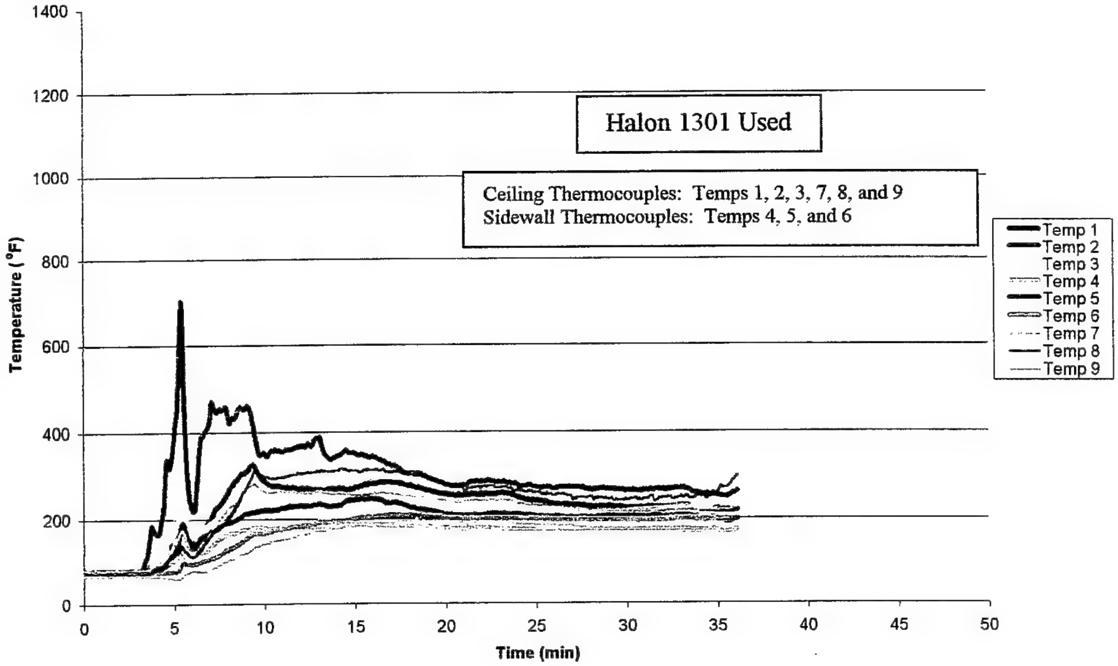


FIGURE 16. BULK-LOAD TEST 7 (082198T3) TEMPERATURE PLOT

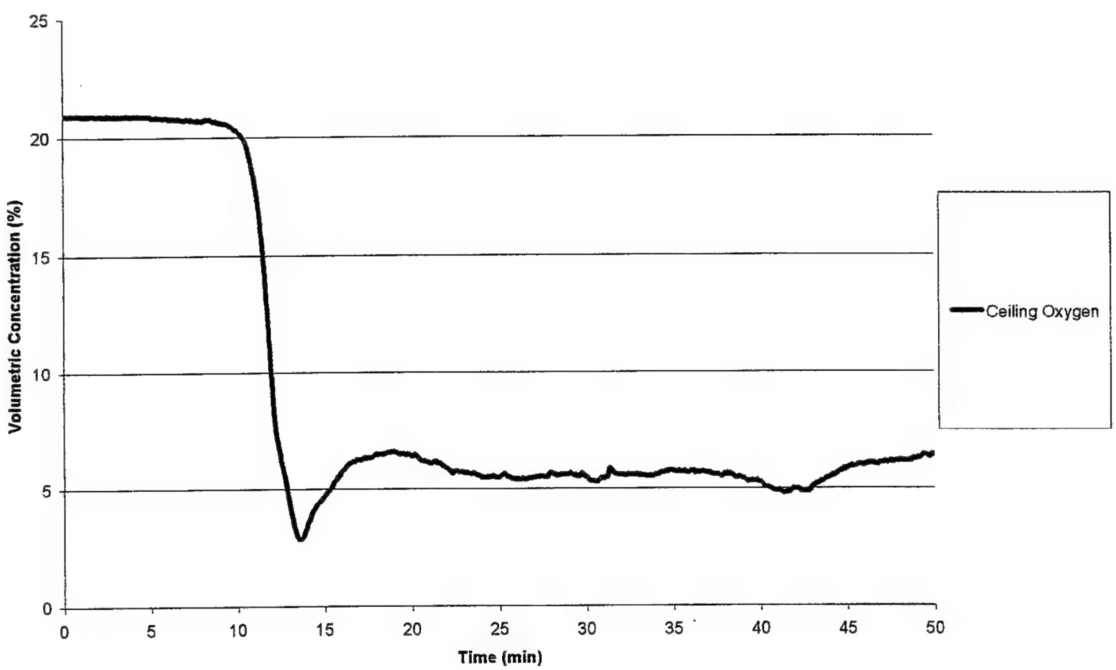


FIGURE 17. BULK-LOAD TEST 1 (091594T1) GAS CONCENTRATION PLOT

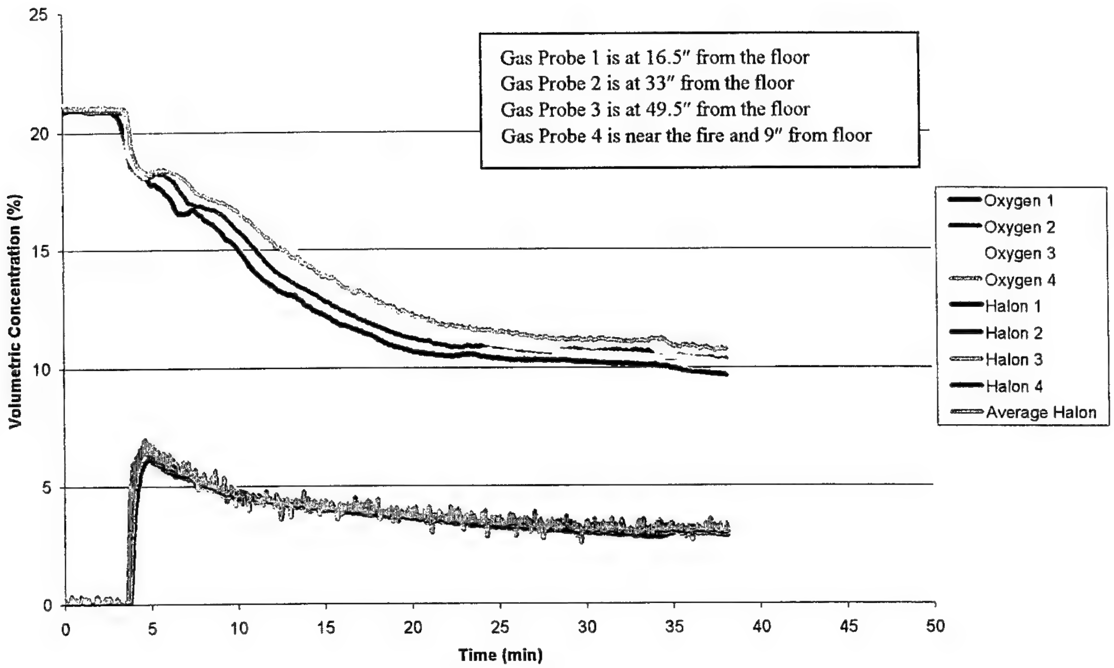


FIGURE 18. BULK-LOAD TEST 2 (081198T1) GAS CONCENTRATION PLOT

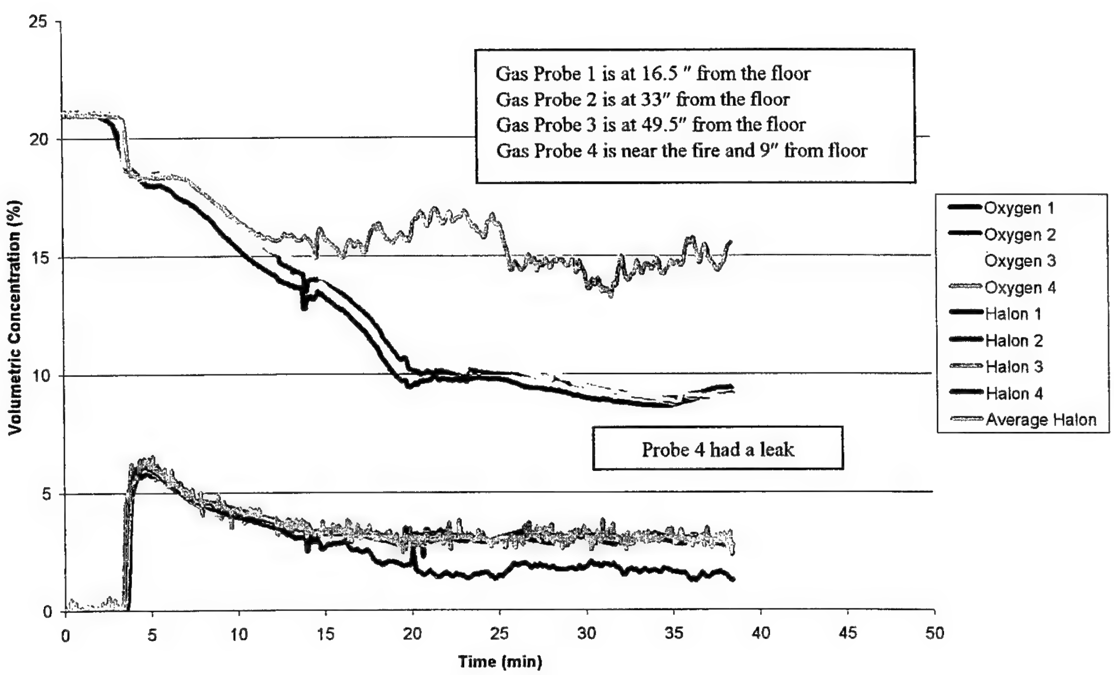


FIGURE 19. BULK-LOAD TEST 3 (081298T1) GAS CONCENTRATION PLOT

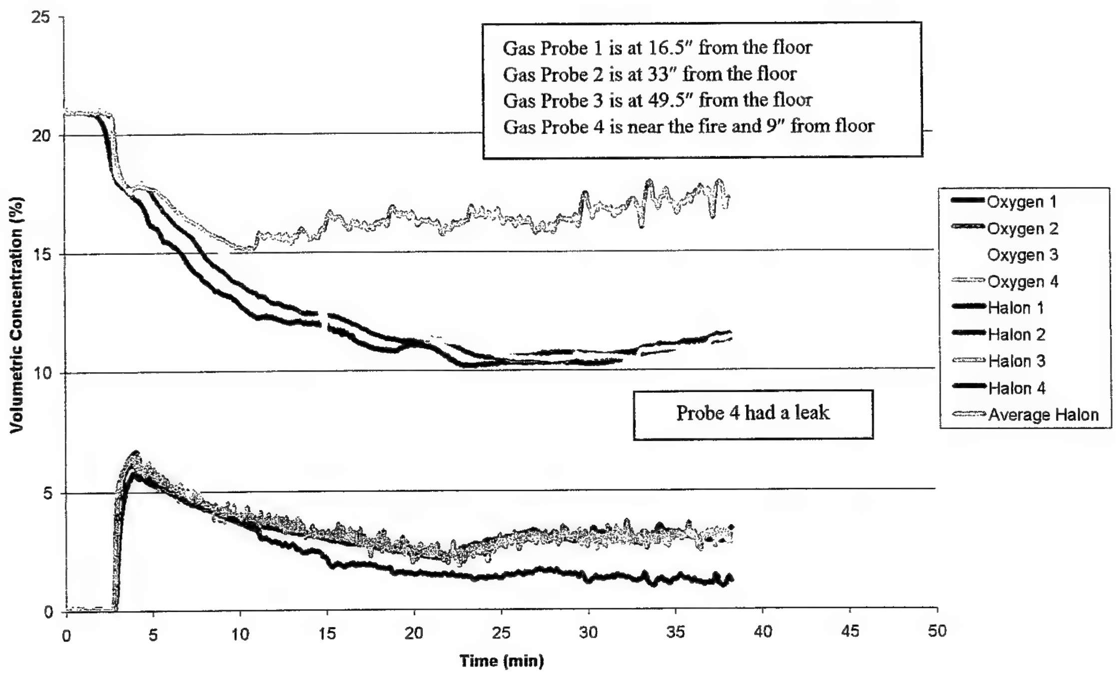


FIGURE 20. BULK-LOAD TEST 4 (081398T2) GAS CONCENTRATION PLOT

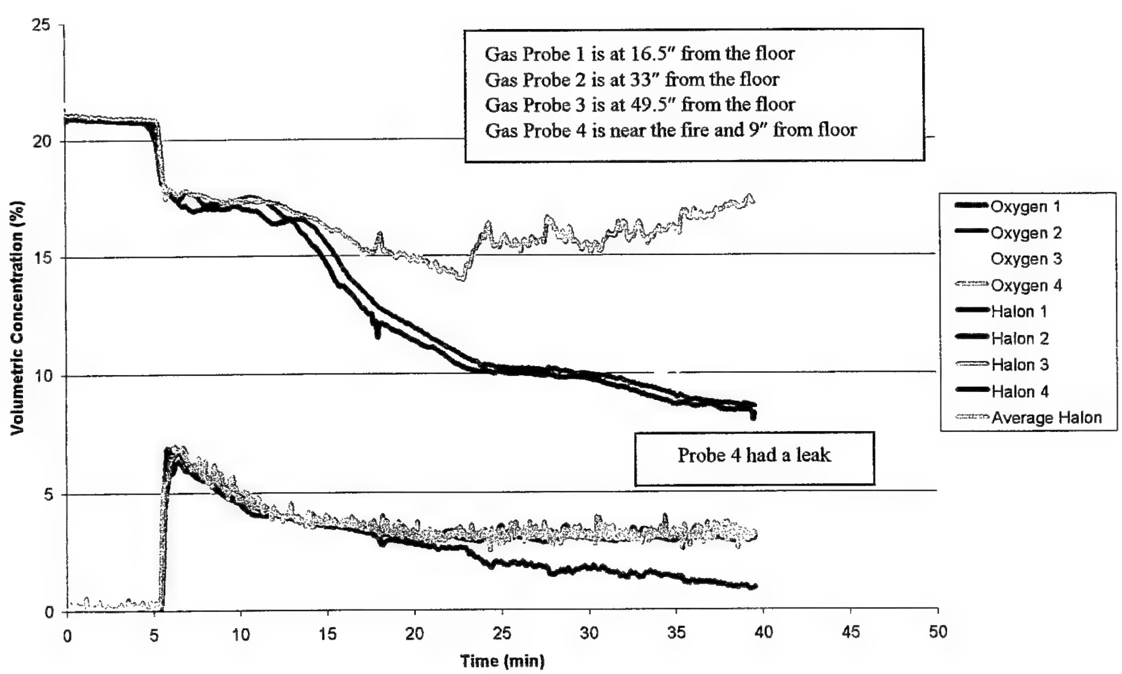


FIGURE 21. BULK-LOAD TEST 5 (081498T1) GAS CONCENTRATION PLOT

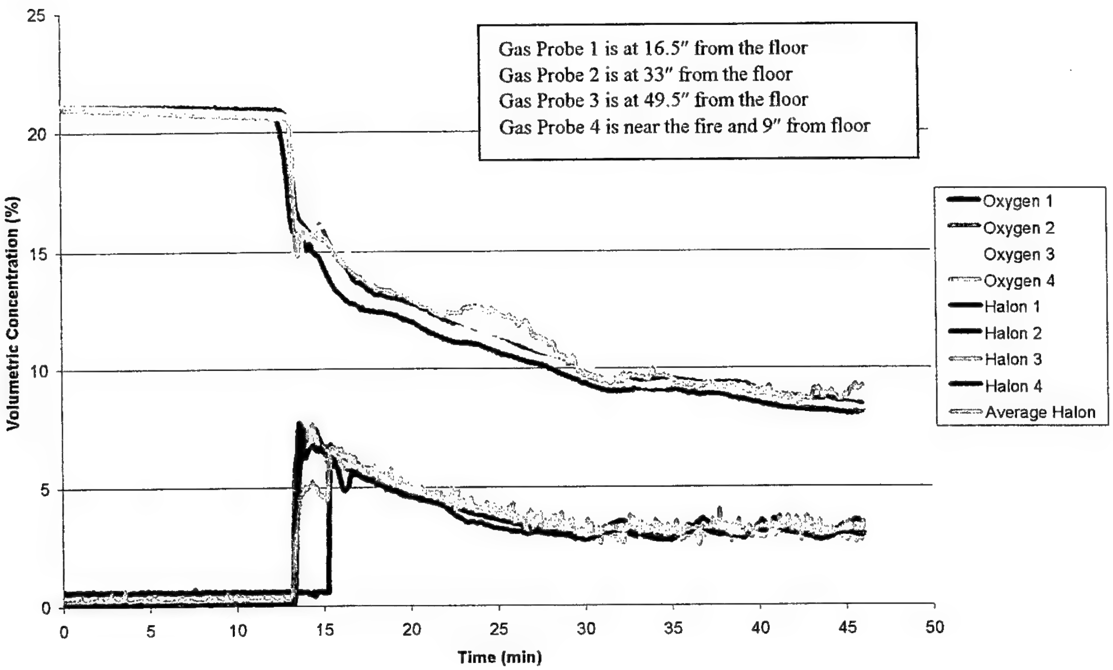


FIGURE 22. BULK-LOAD TEST 6 (081998T1) GAS CONCENTRATION PLOT

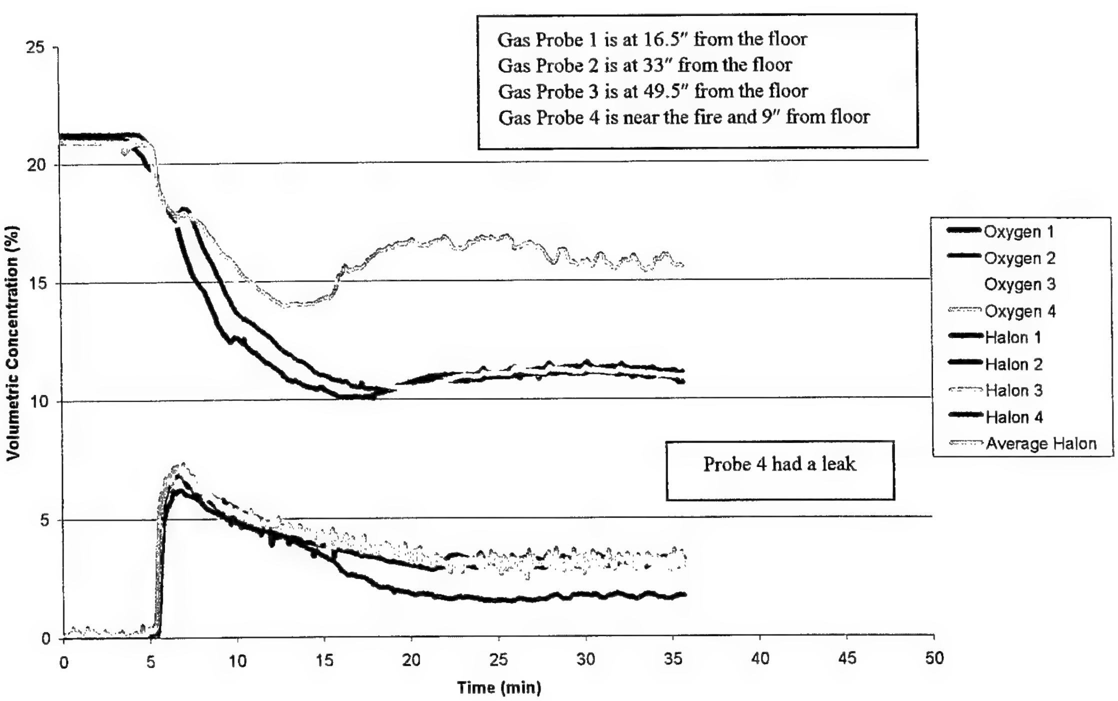


FIGURE 23. BULK-LOAD TEST 7 (082198T3) GAS CONCENTRATION PLOT

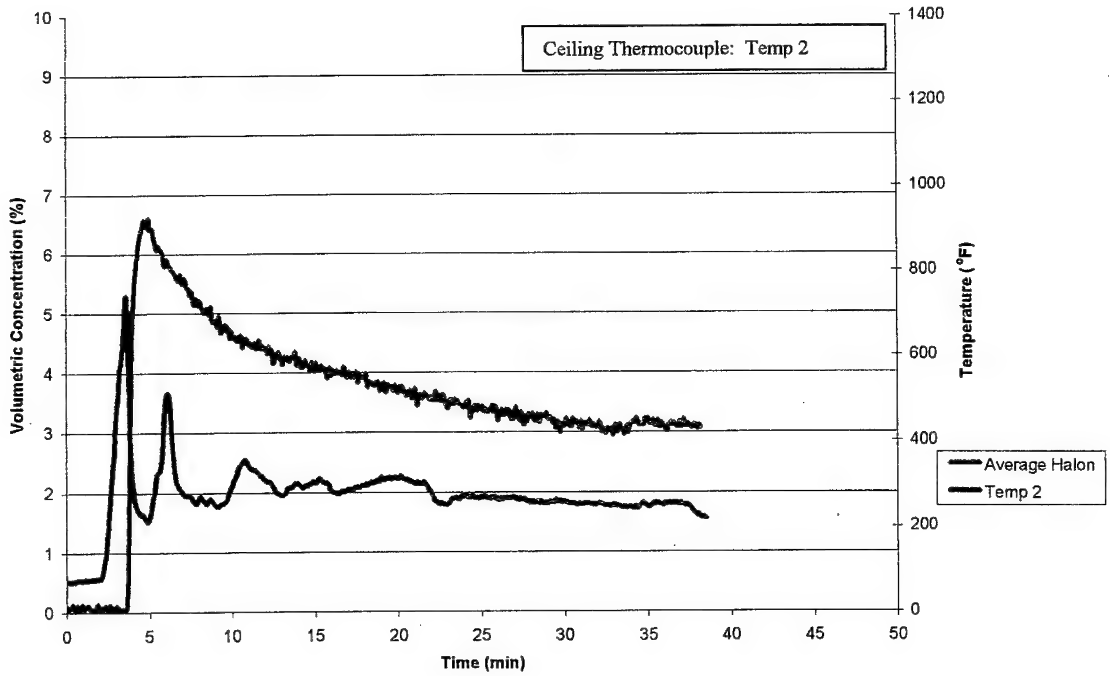


FIGURE 24. HALON 1301 VS TEMPERATURE DURING BULK-LOAD TEST 2 (081198T1)

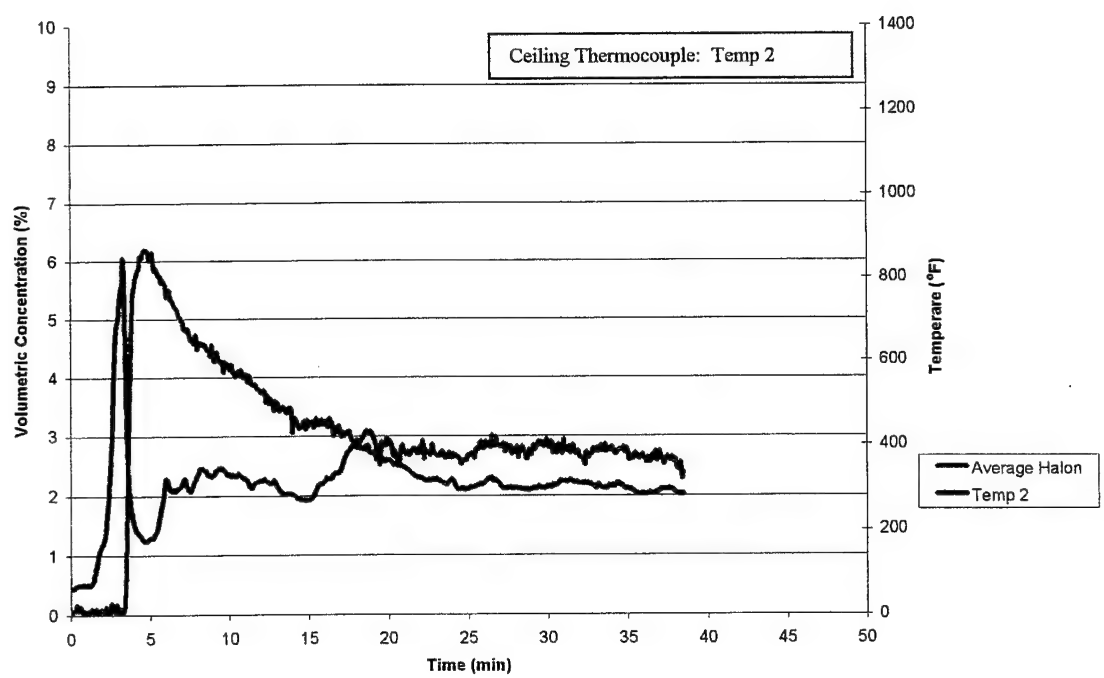


FIGURE 25. HALON 1301 VS TEMPERATURE DURING BULK-LOAD TEST 3 (081298T1)

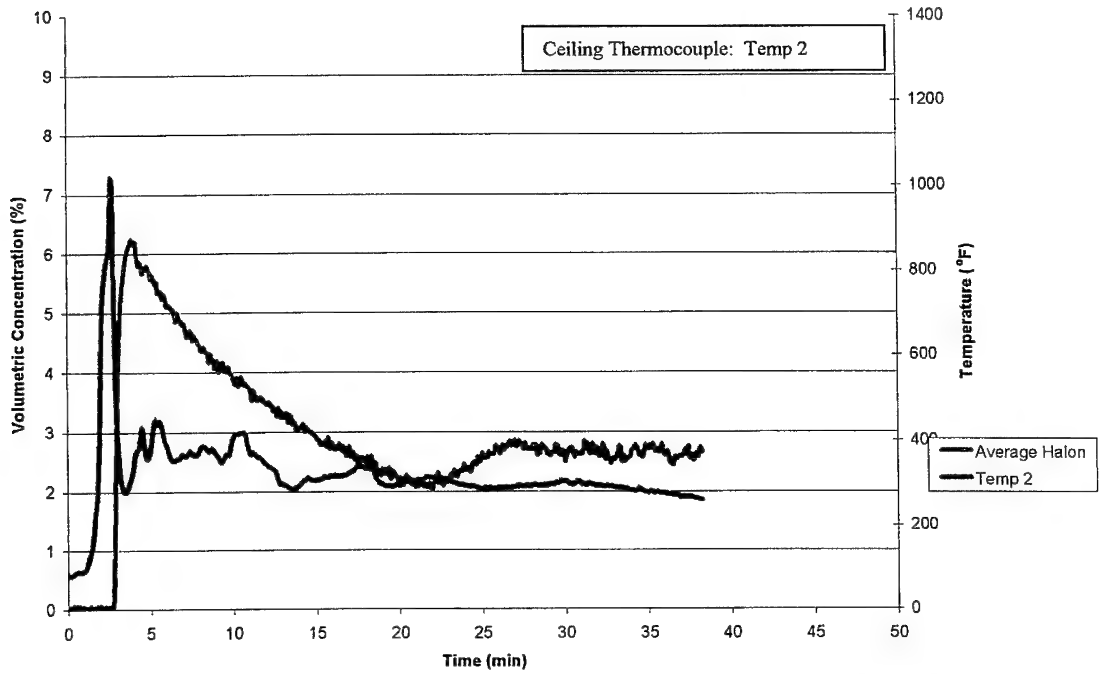


FIGURE 26. HALON 1301 VS TEMPERATURE DURING BULK-LOAD TEST 4 (081398T2)

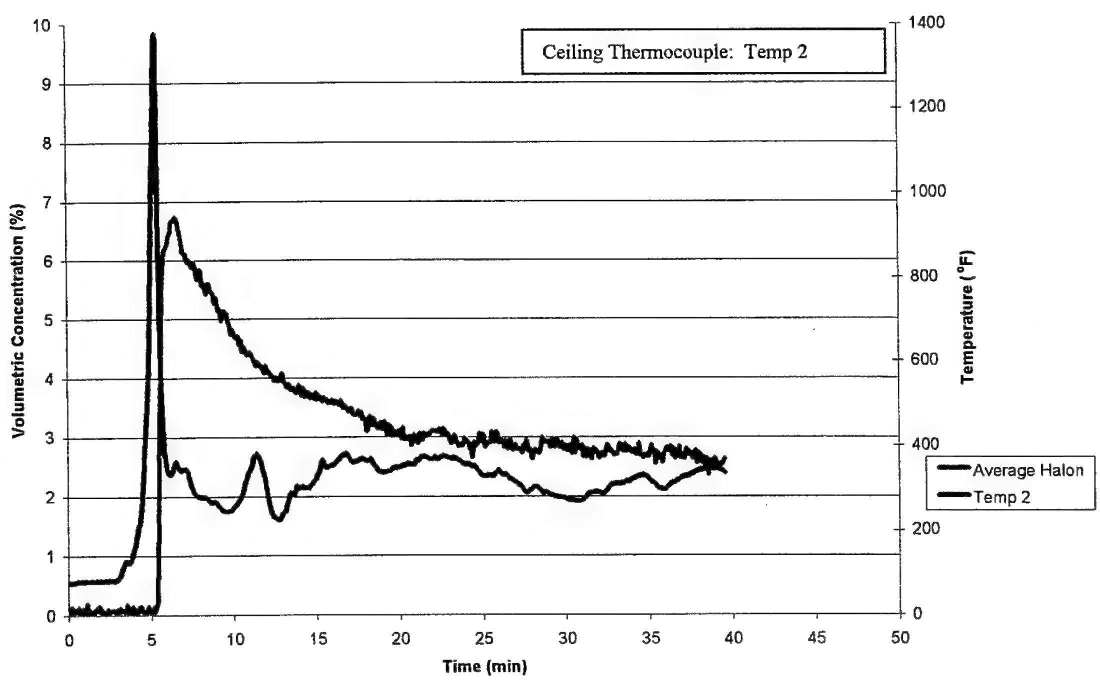


FIGURE 27. HALON 1301 VS TEMPERATURE DURING BULK-LOAD TEST 5 (081498T1)

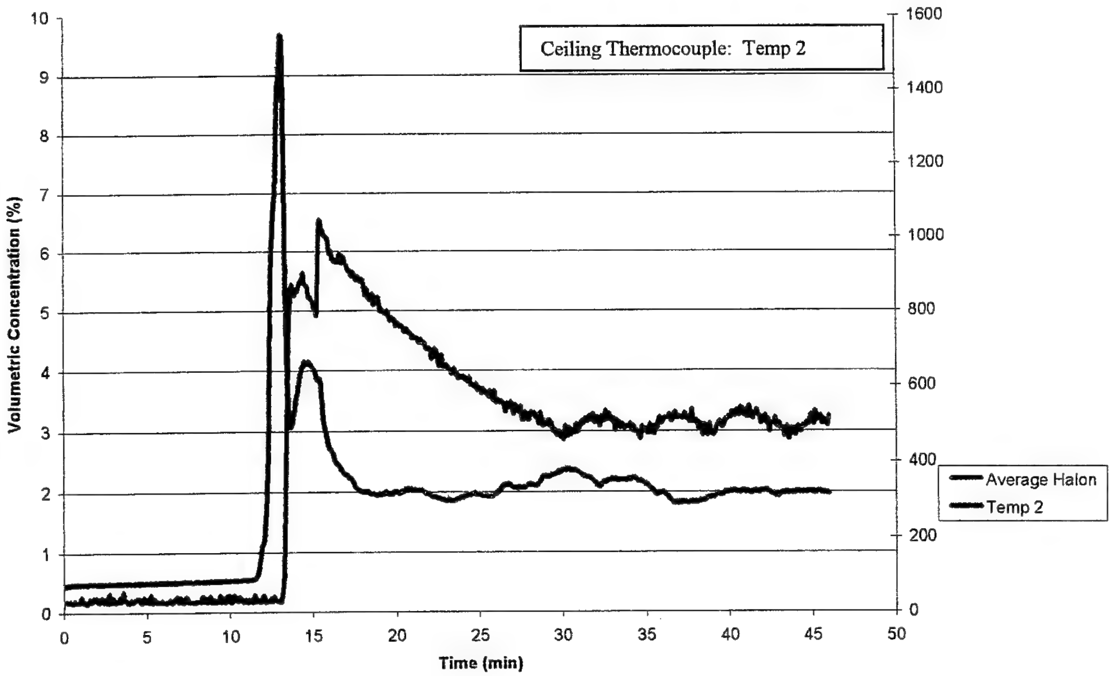


FIGURE 28. HALON 1301 VS TEMPERATURE DURING BULK-LOAD TEST 6 (081998T1)

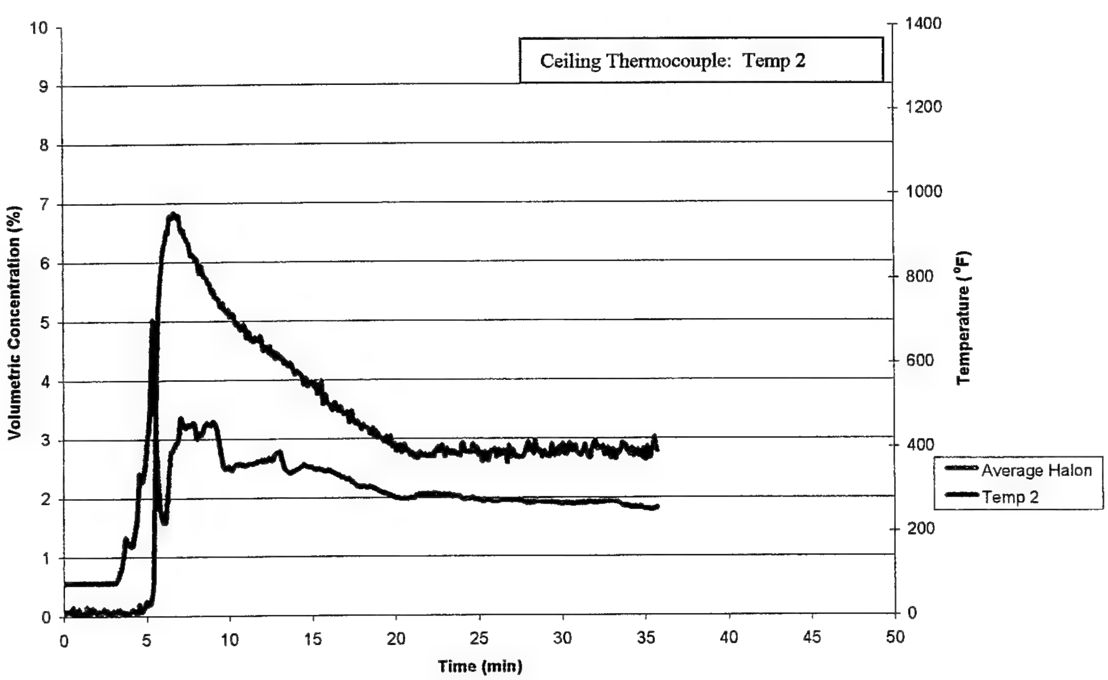


FIGURE 29. HALON 1301 VS TEMPERATURE DURING BULK-LOAD TEST 7 (082198T3)

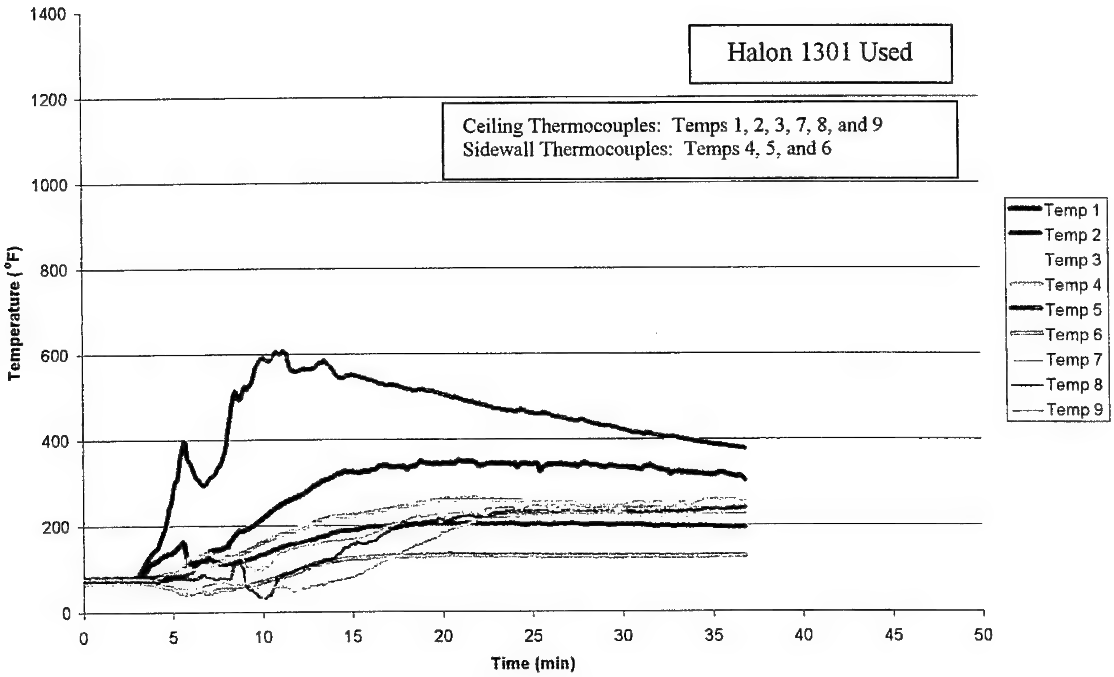


FIGURE 30. CONTAINERIZED TEST 8 (082898T1) TEMPERATURE PLOT

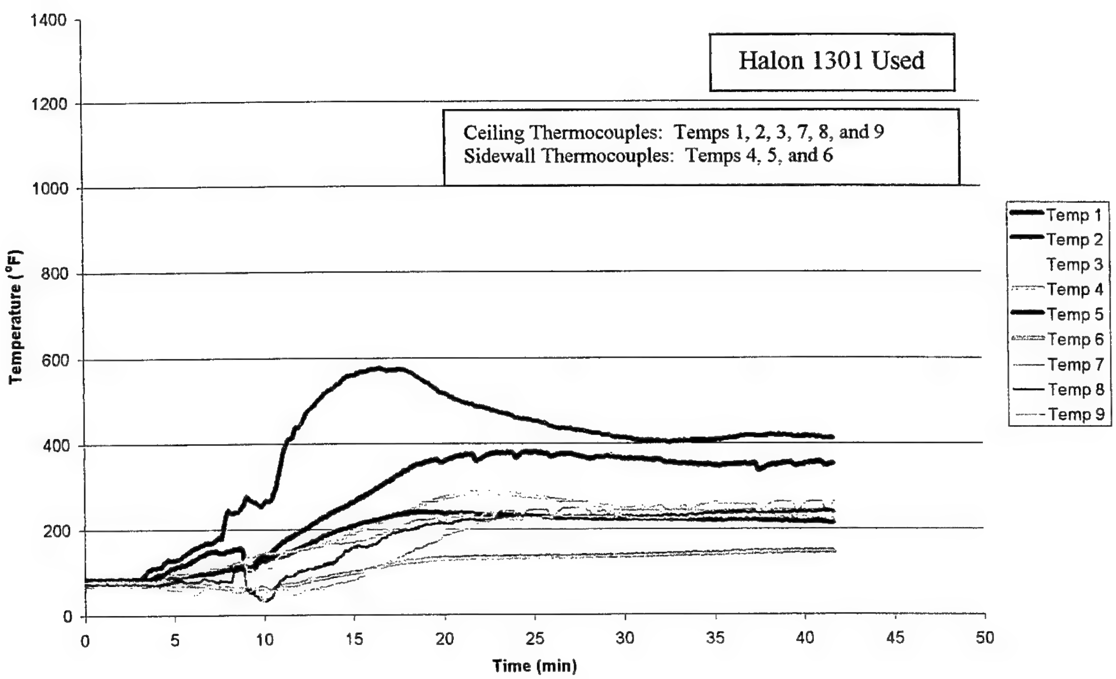


FIGURE 31. CONTAINERIZED TEST 9 (083198T1) TEMPERATURE PLOT

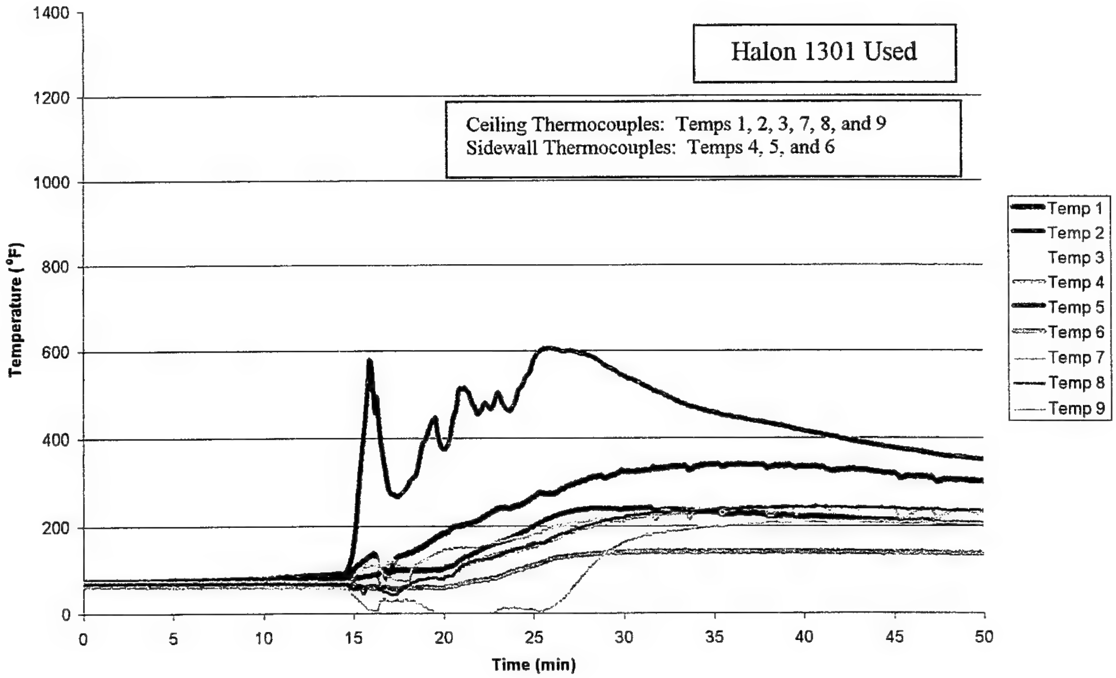


FIGURE 32. CONTAINERIZED TEST 10 (090198T1) TEMPERATURE PLOT

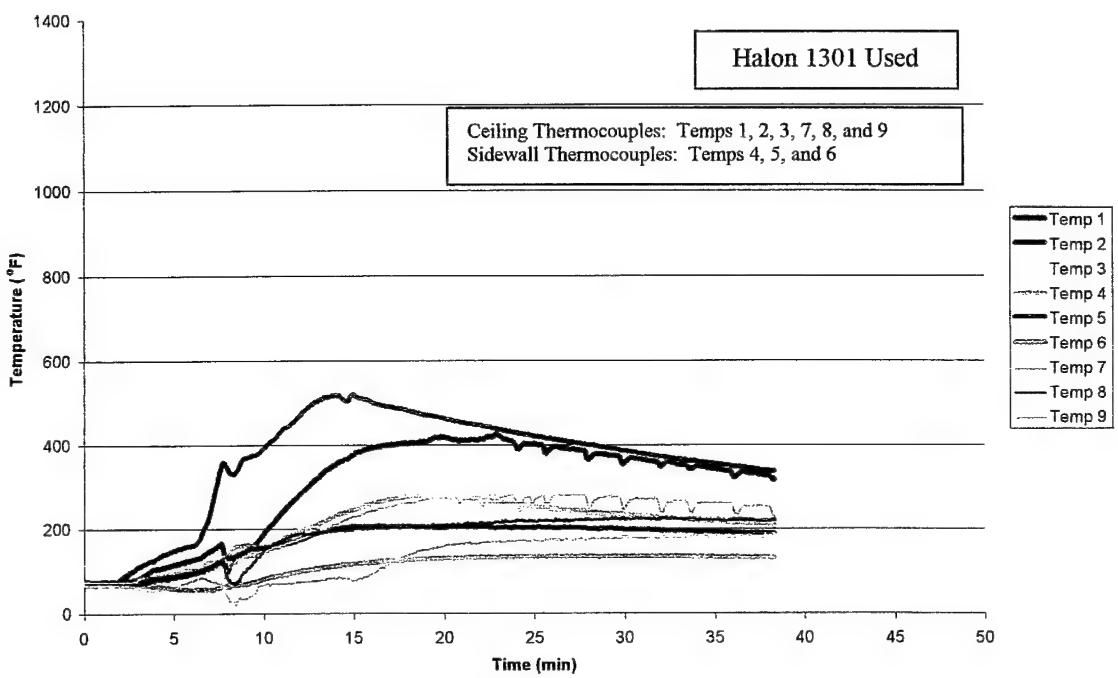


FIGURE 33. CONTAINERIZED TEST 11 (090298T1) TEMPERATURE PLOT

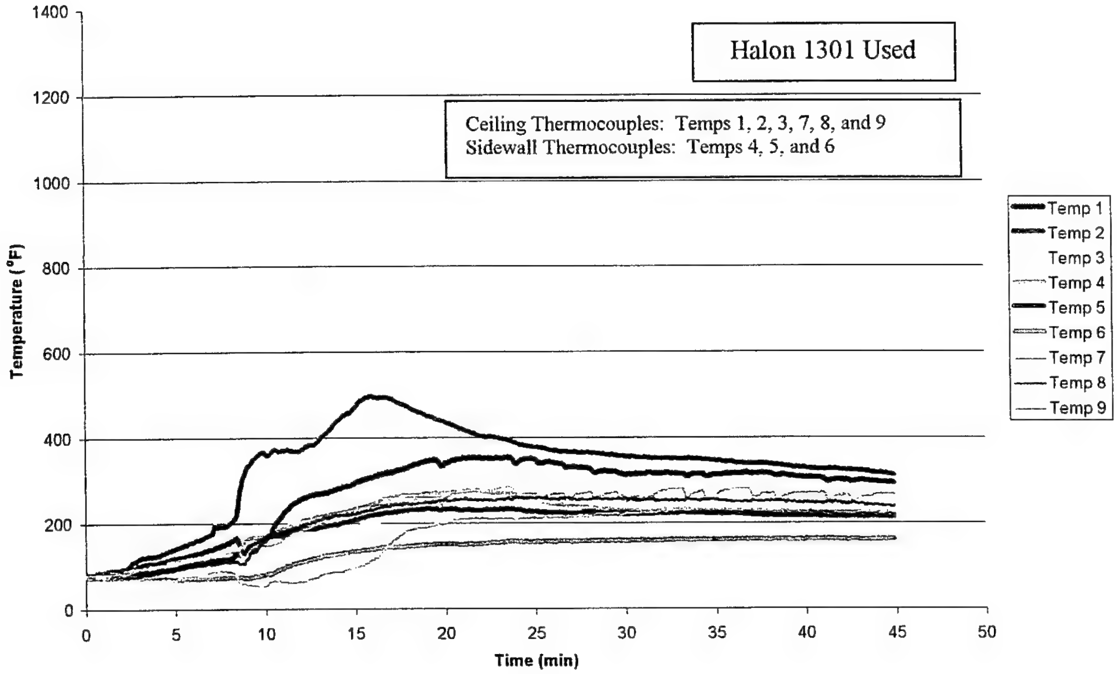


FIGURE 34. CONTAINERIZED TEST 12 (090498T1) TEMPERATURE PLOT

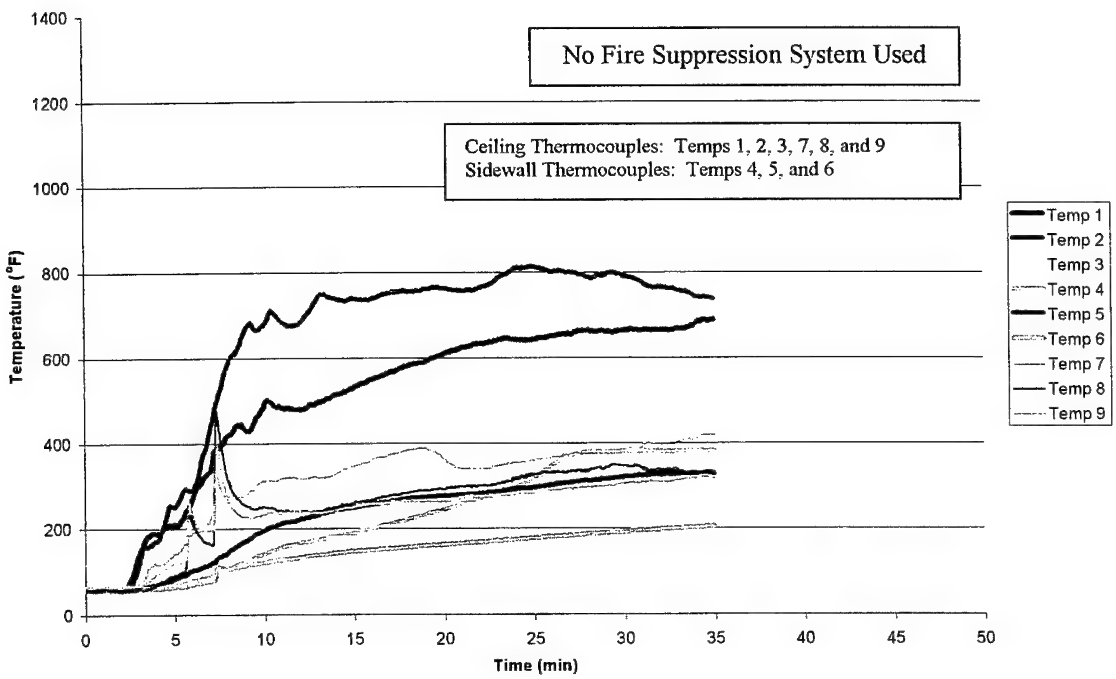


FIGURE 35. CONTAINERIZED TEST 13 (110998T1) TEMPERATURE PLOT

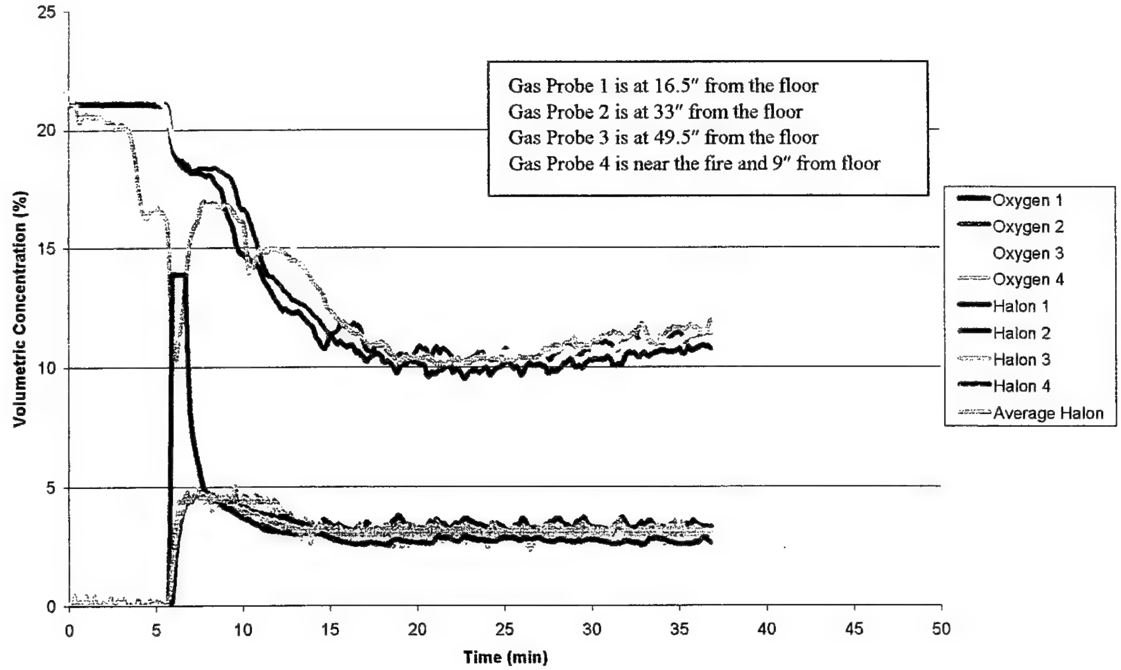


FIGURE 36. CONTAINERIZED TEST 8 (082898T1) GAS CONCENTRATION PLOT

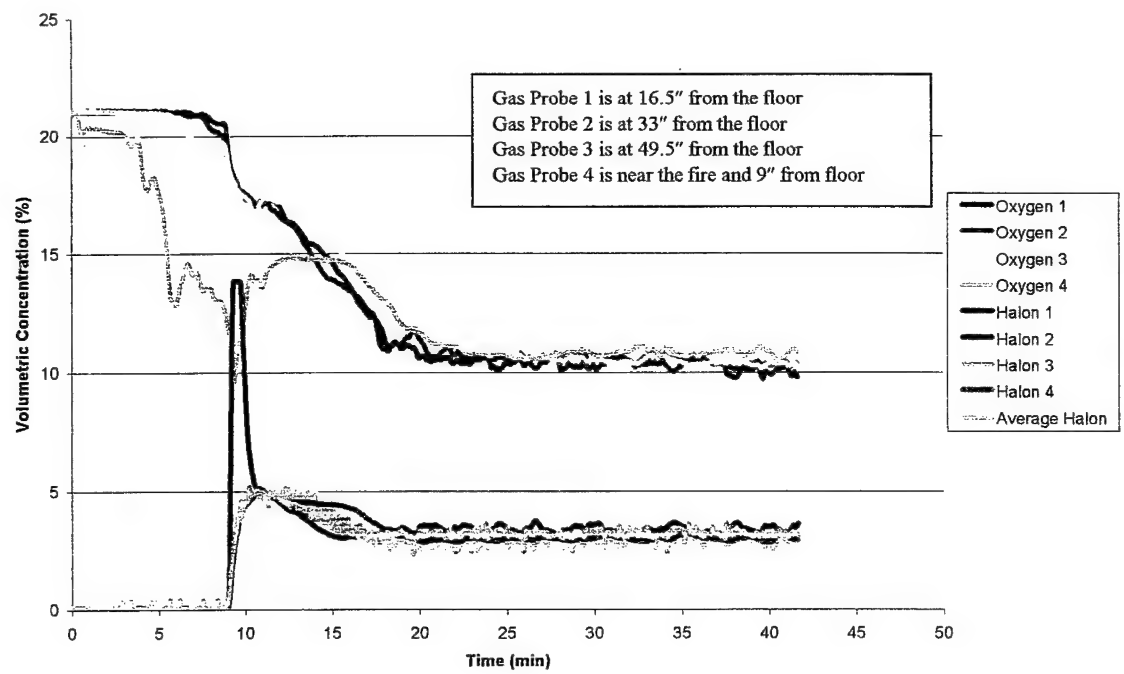


FIGURE 37. CONTAINERIZED TEST 9 (083198T1) GAS CONCENTRATION PLOT

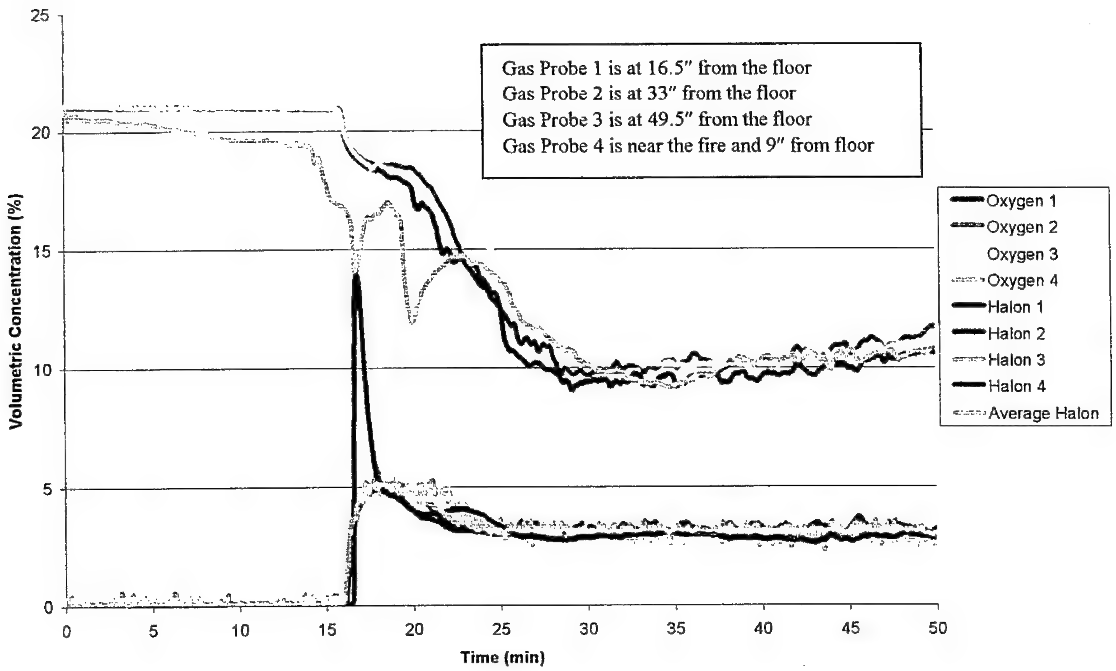


FIGURE 38. CONTAINERIZED TEST 10 (090198T1) GAS CONCENTRATION PLOT

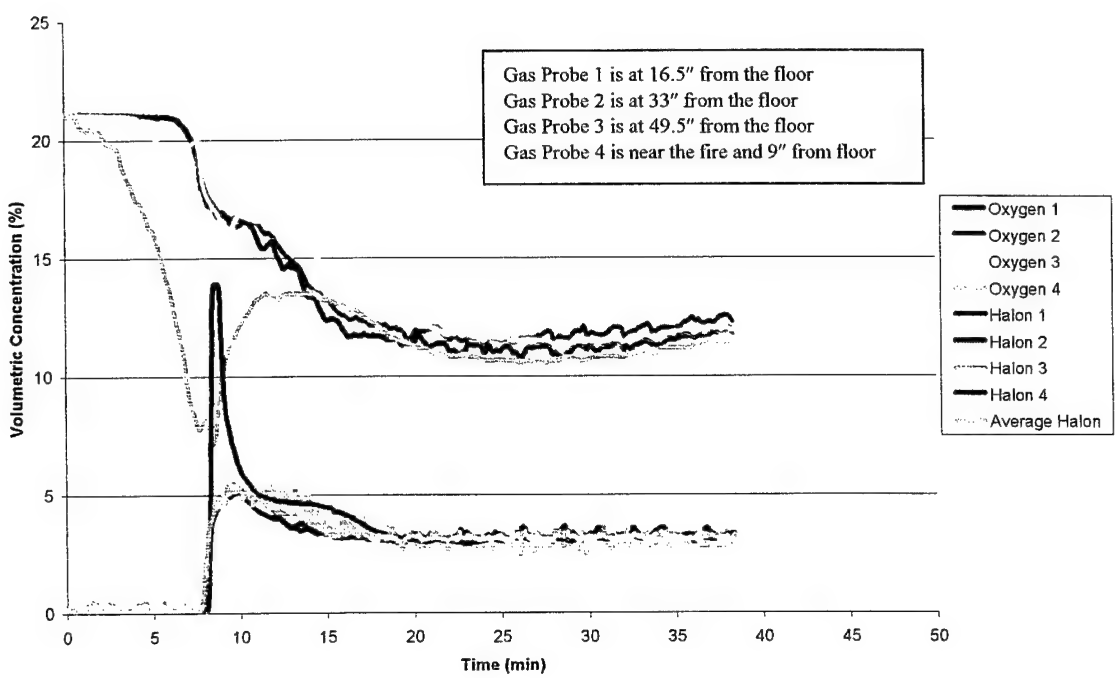


FIGURE 39. CONTAINERIZED TEST 11 (090298T1) GAS CONCENTRATION PLOT

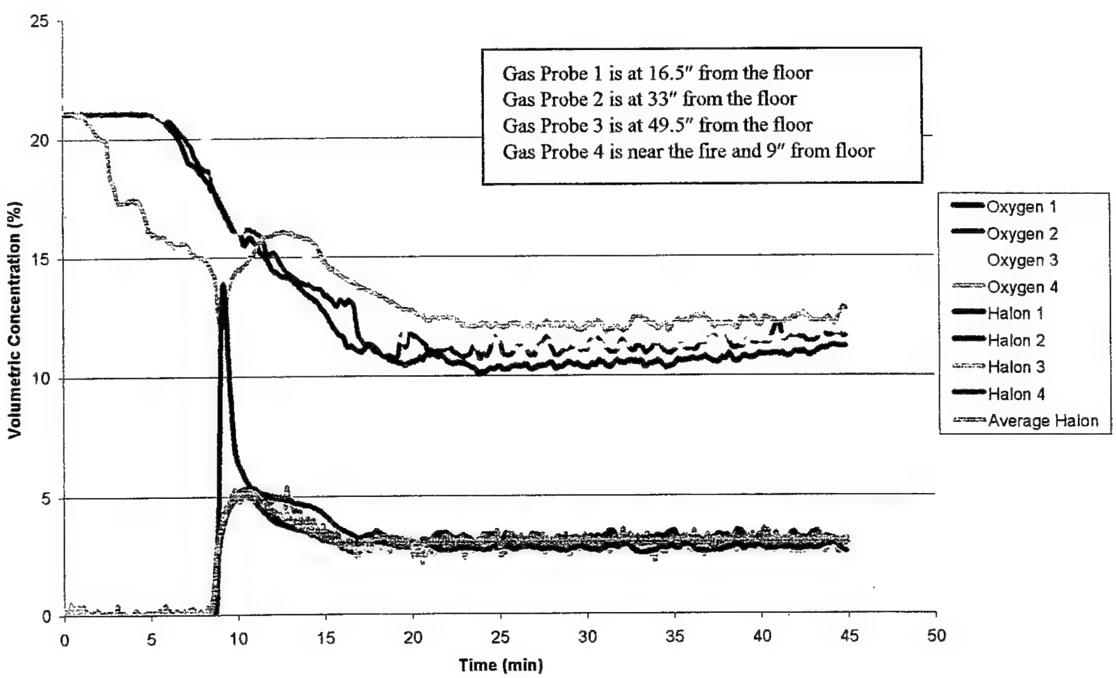


FIGURE 40. CONTAINERIZED TEST 12 (090498T1) GAS CONCENTRATION PLOT

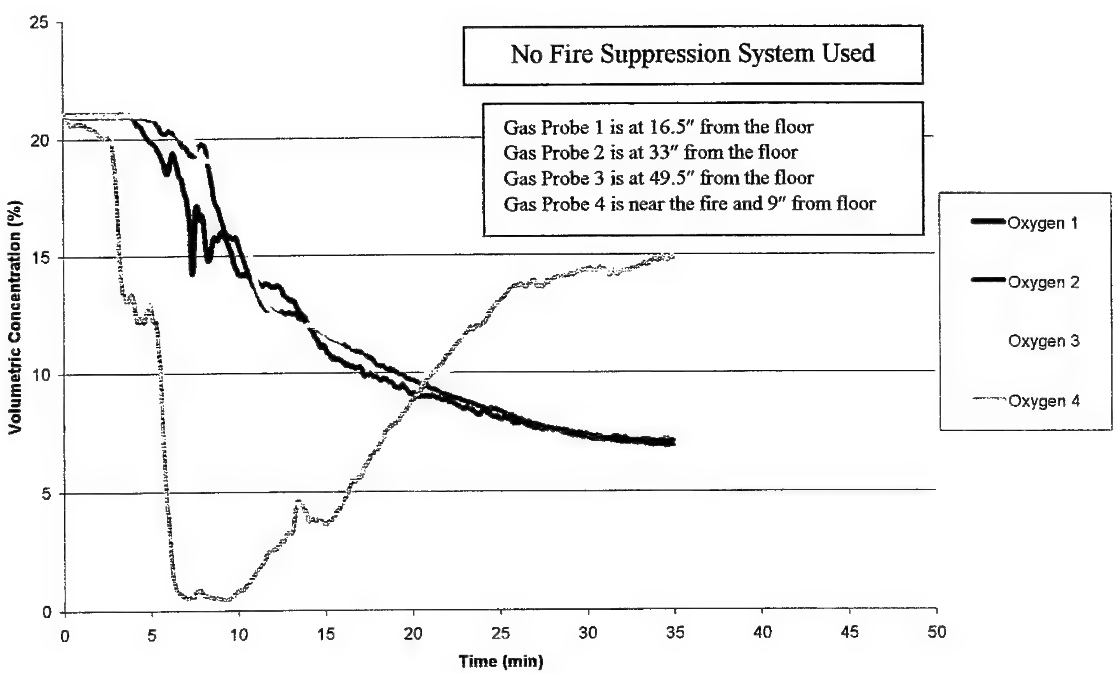


FIGURE 41. CONTAINERIZED TEST 13 (110998T1) GAS CONCENTRATION PLOT

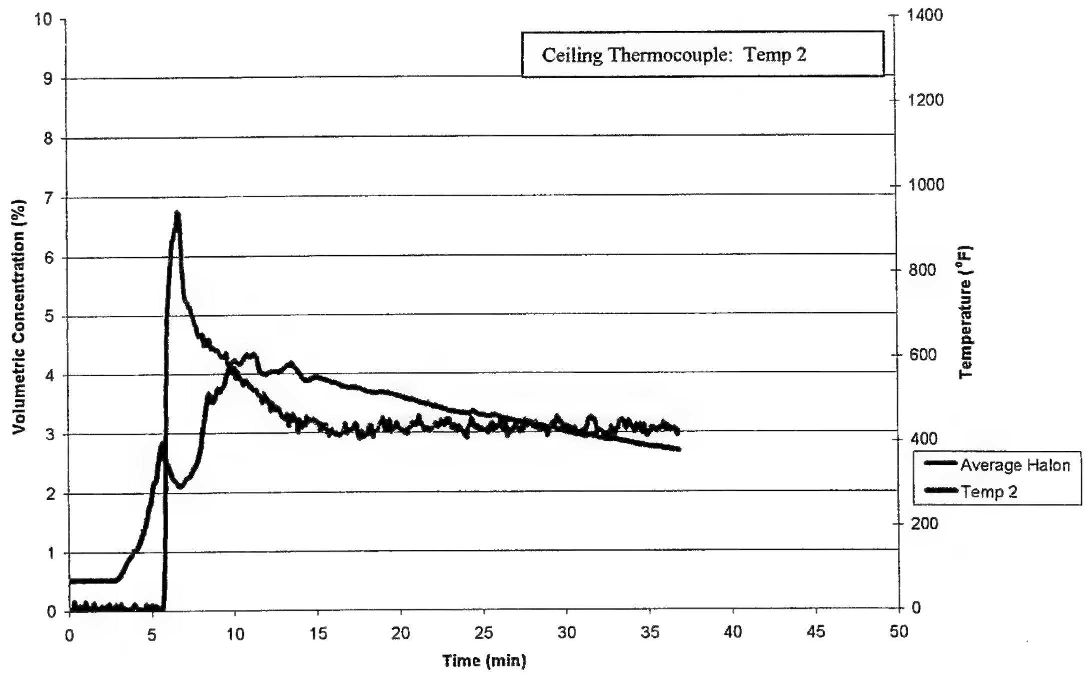


FIGURE 42. HALON 1301 VS TEMPERATURE DURING CONTAINERIZED TEST 8 (082898T1)

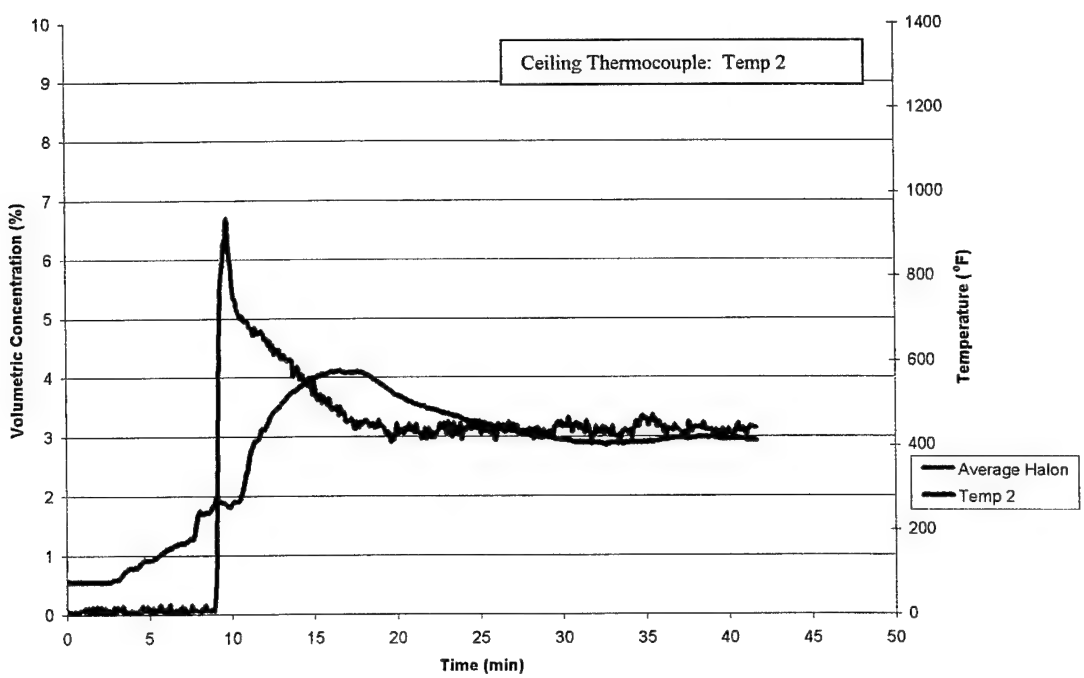


FIGURE 43. HALON 1301 VS TEMPERATURE DURING CONTAINERIZED TEST 9 (083198T1)

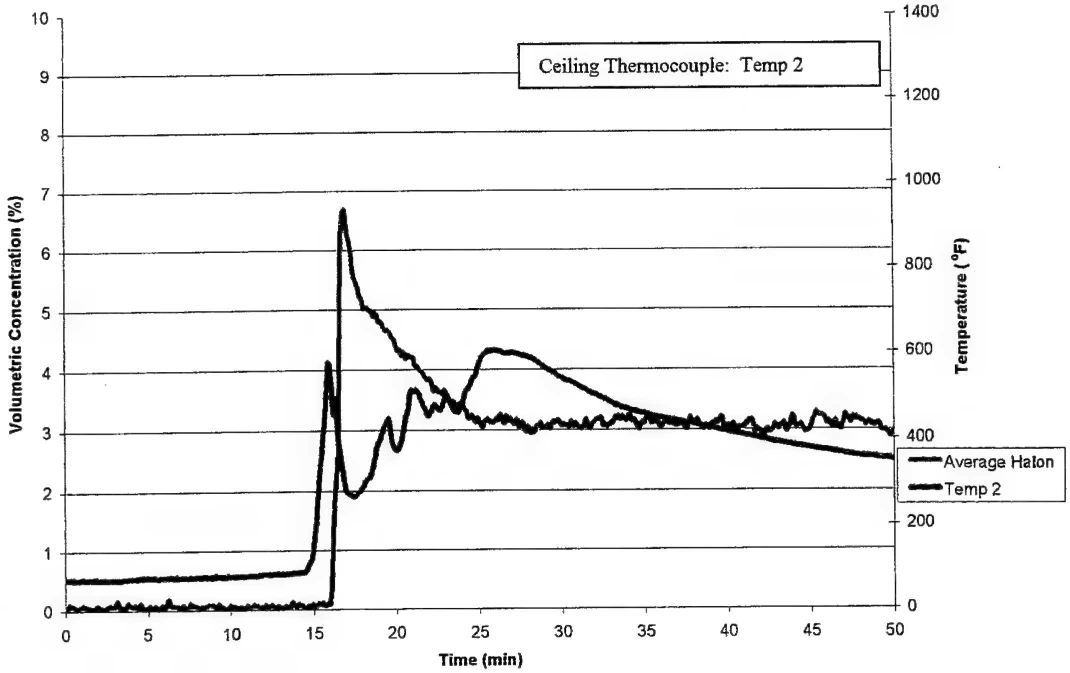


FIGURE 44. HALON 1301 VS TEMPERATURE DURING CONTAINERIZED TEST 10 (090198T1)

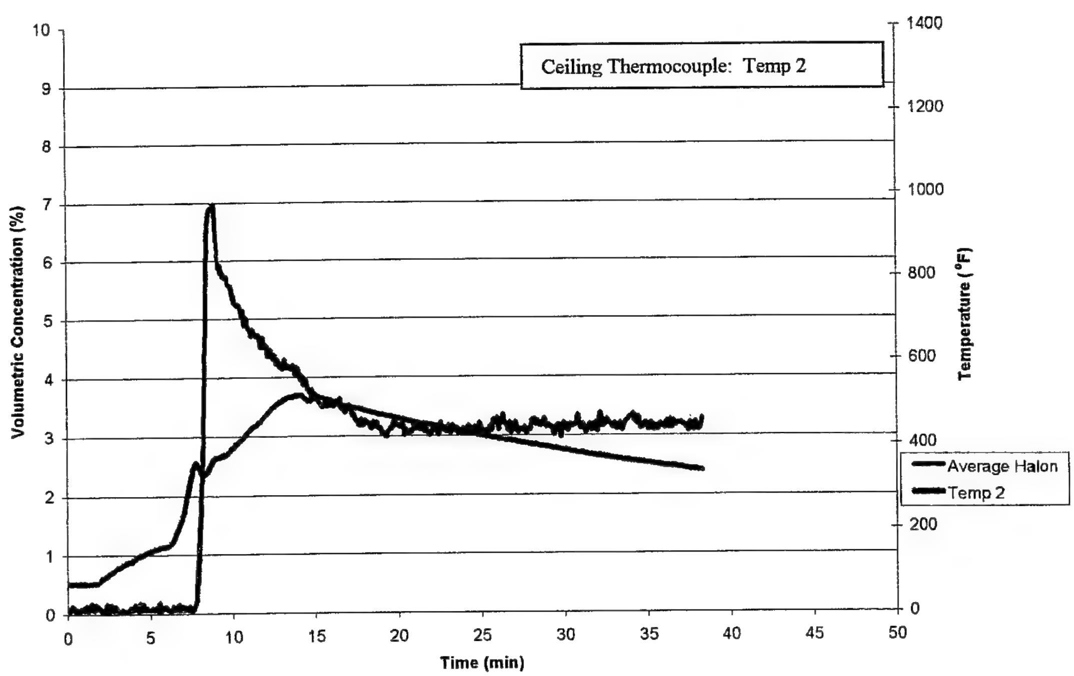


FIGURE 45. HALON 1301 VS TEMPERATURE DURING CONTAINERIZED TEST 11 (090298T1)

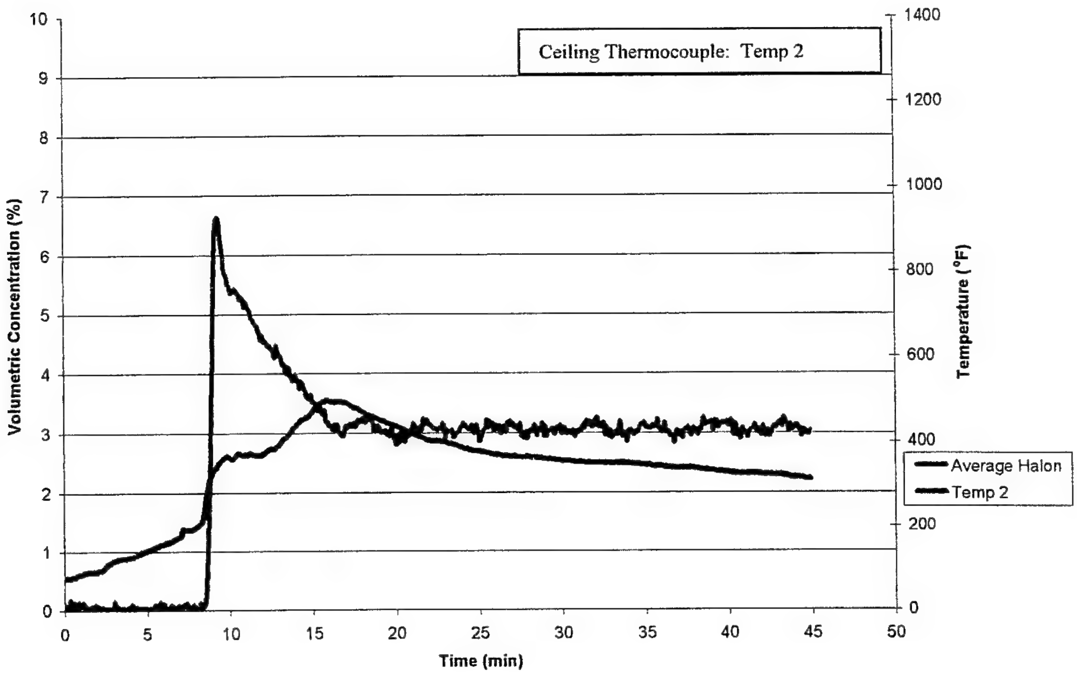


FIGURE 46. HALON 1301 VS TEMPERATURE DURING CONTAINERIZED TEST 12 (090498T1)

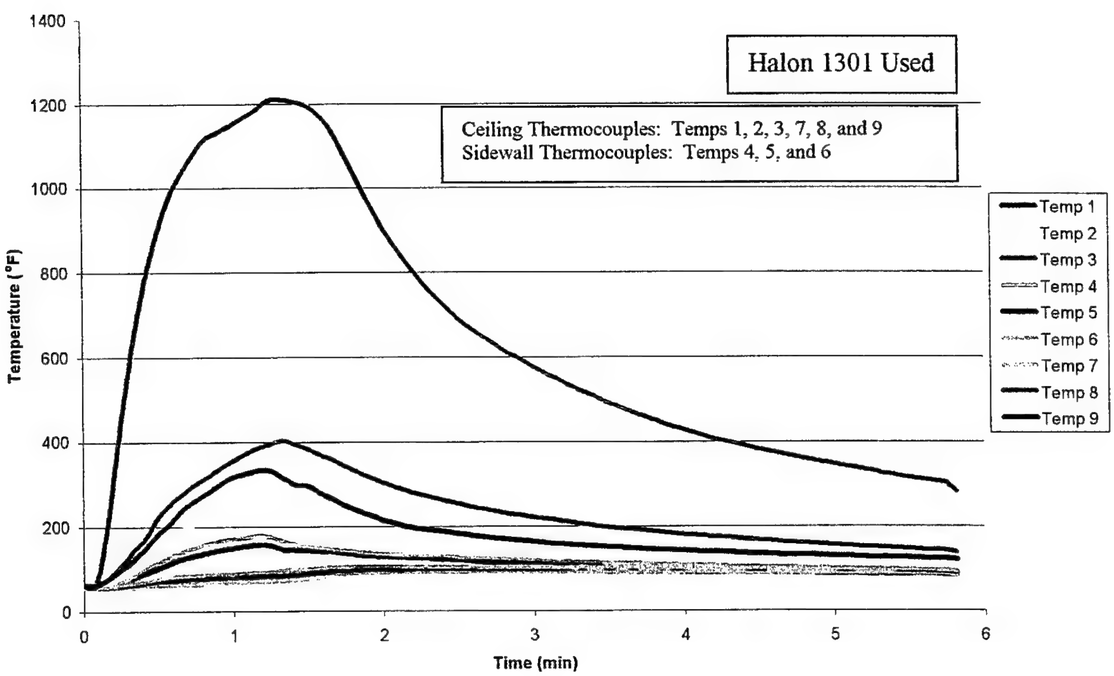


FIGURE 47. SURFACE BURN TEST 14 (111899T3) TEMPERATURE PLOT

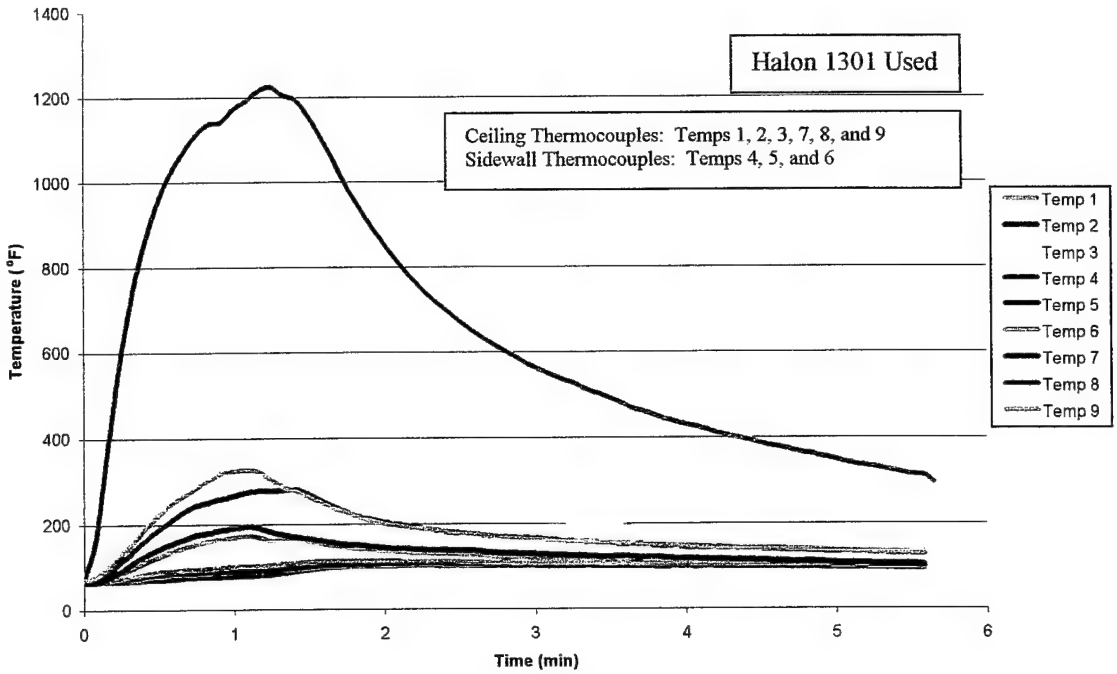


FIGURE 48. SURFACE BURN TEST 15 (111899T4) TEMPERATURE PLOT

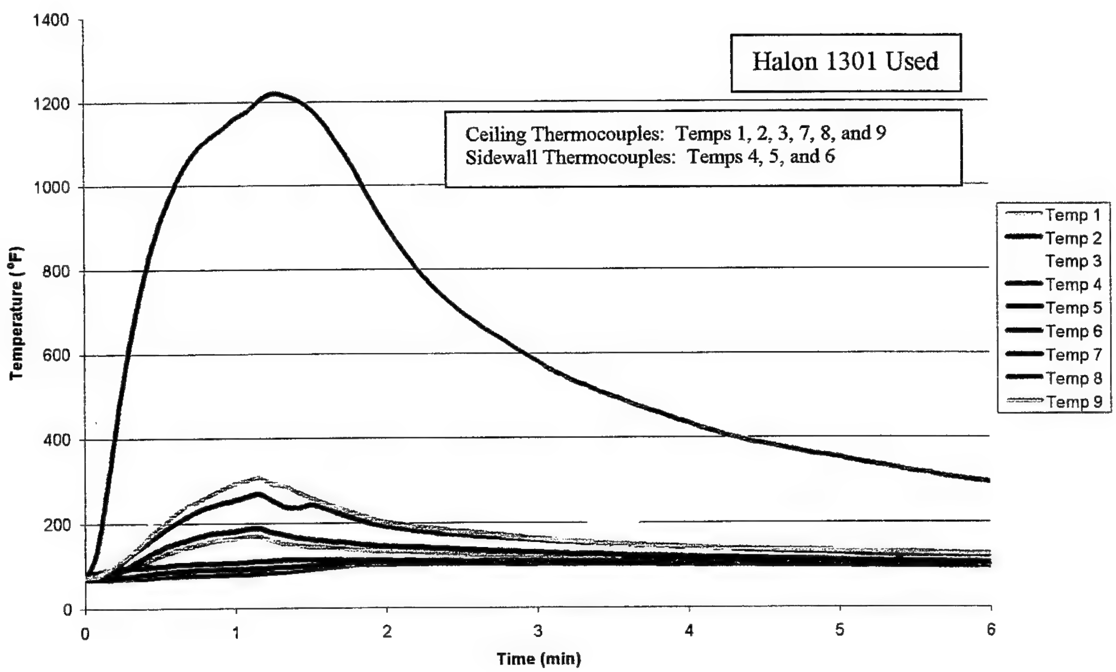


FIGURE 49. SURFACE BURN TEST 16 (111999T1) TEMPERATURE PLOT

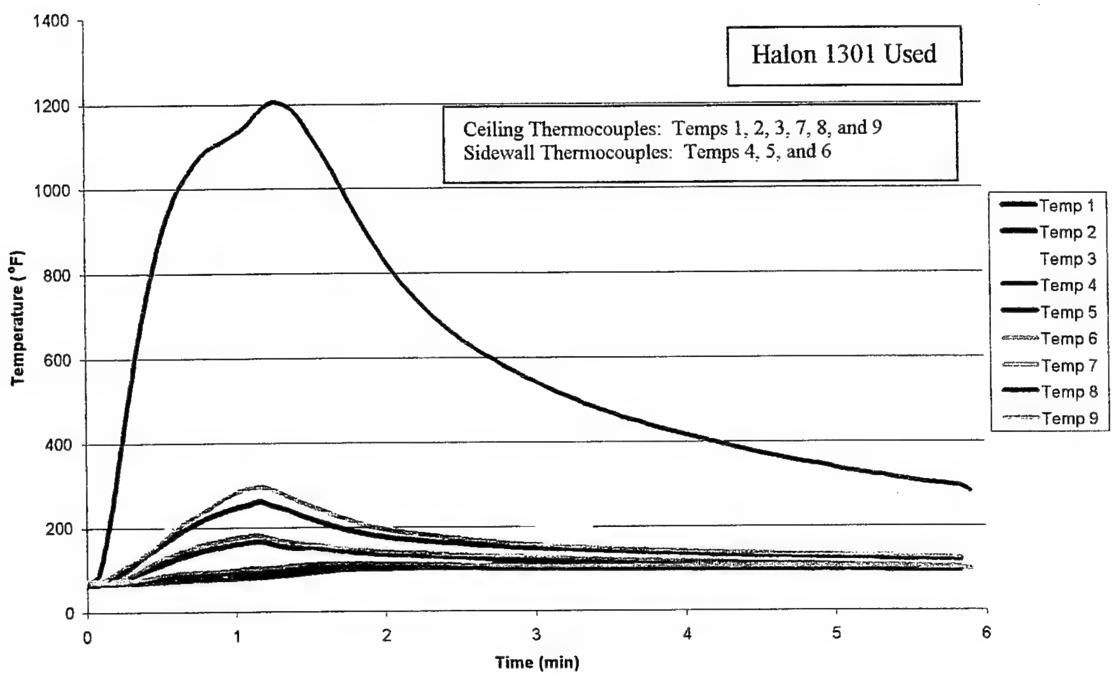


FIGURE 50. SURFACE BURN TEST 17 (111999T2) TEMPERATURE PLOT

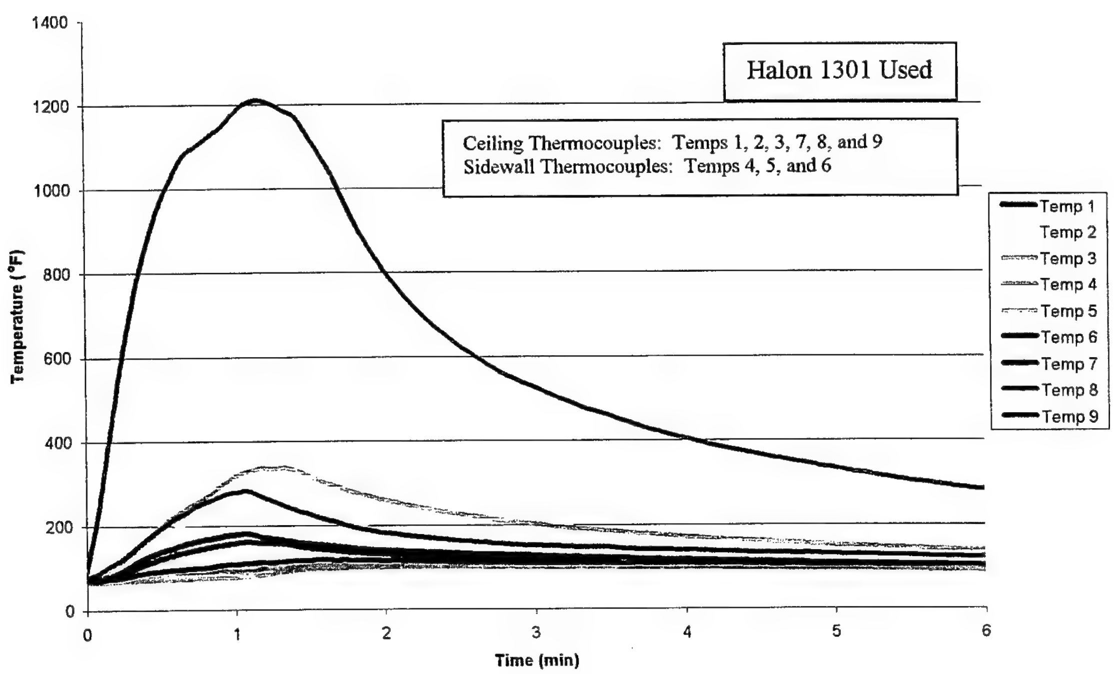


FIGURE 51. SURFACE BURN TEST 18 (111999T3) TEMPERATURE PLOT

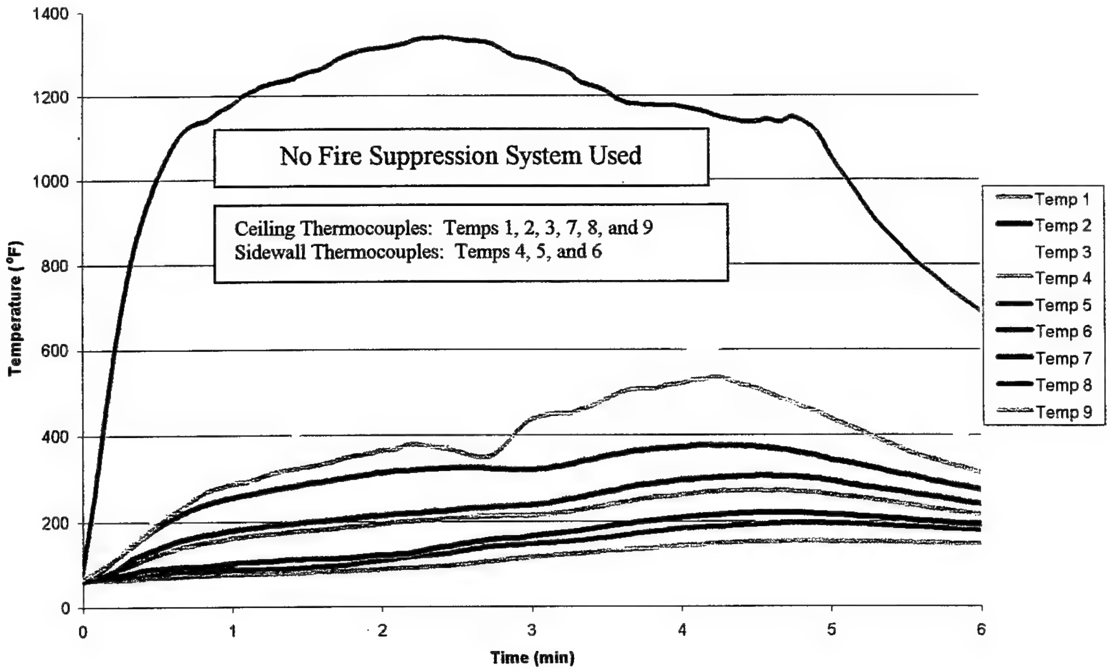


FIGURE 52. SURFACE BURN TEST 19 (111999T4) TEMPERATURE PLOT

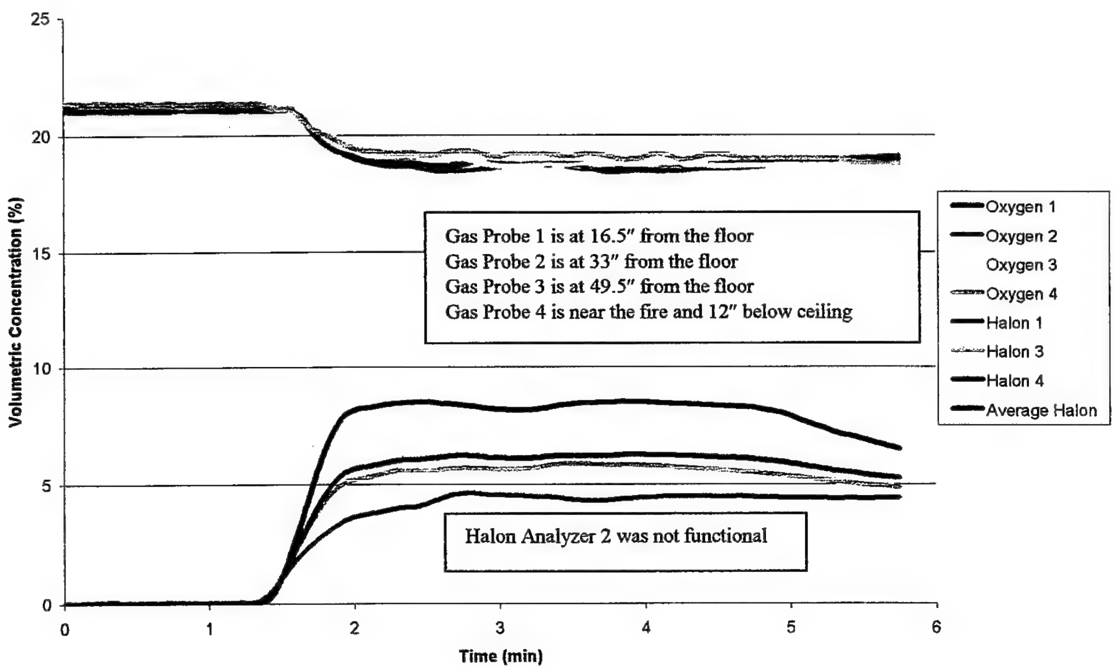


FIGURE 53. SURFACE BURN TEST 14 (111899T3) GAS CONCENTRATION PLOT

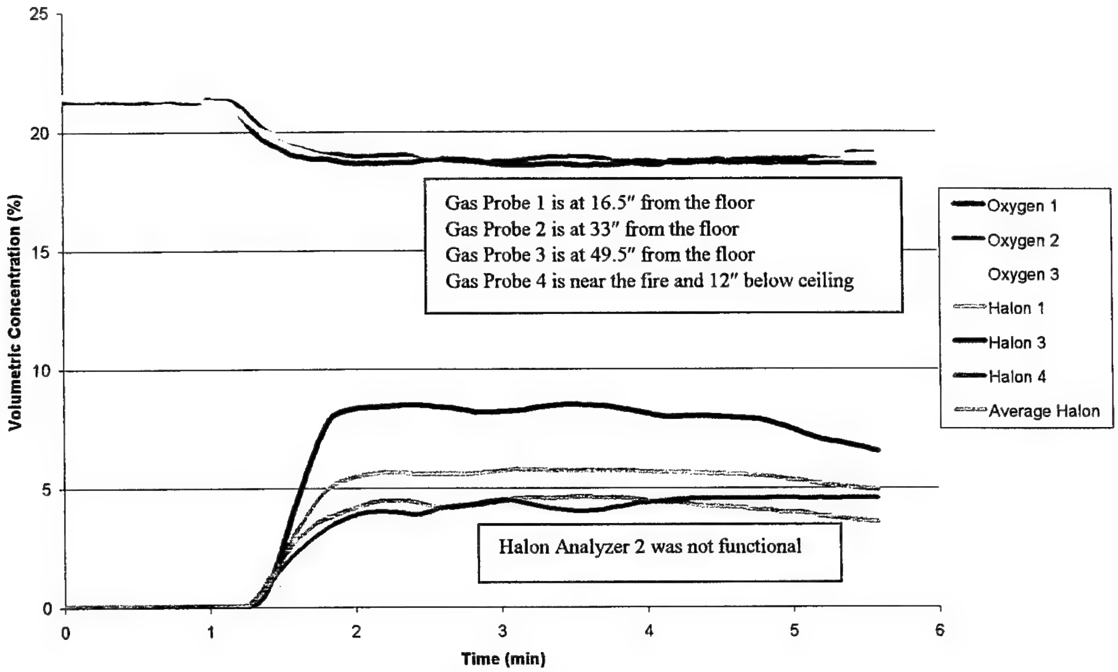


FIGURE 54. SURFACE BURN TEST 15 (111899T4) GAS CONCENTRATION PLOT

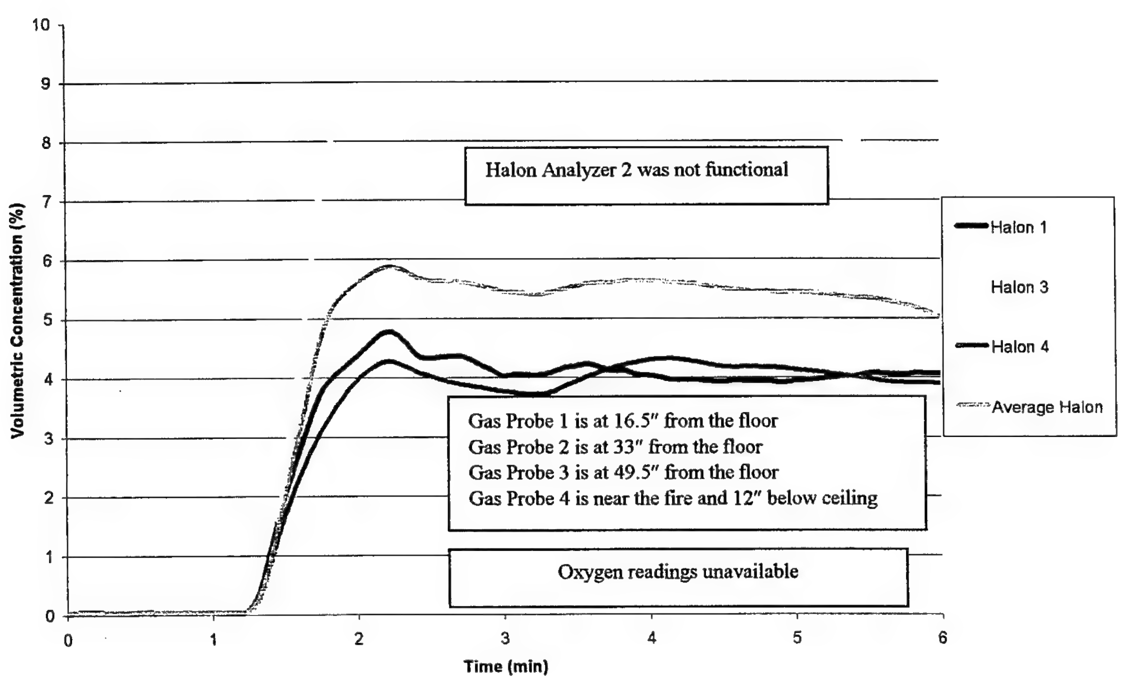


FIGURE 55. SURFACE BURN TEST 16 (111999T1) GAS CONCENTRATION PLOT

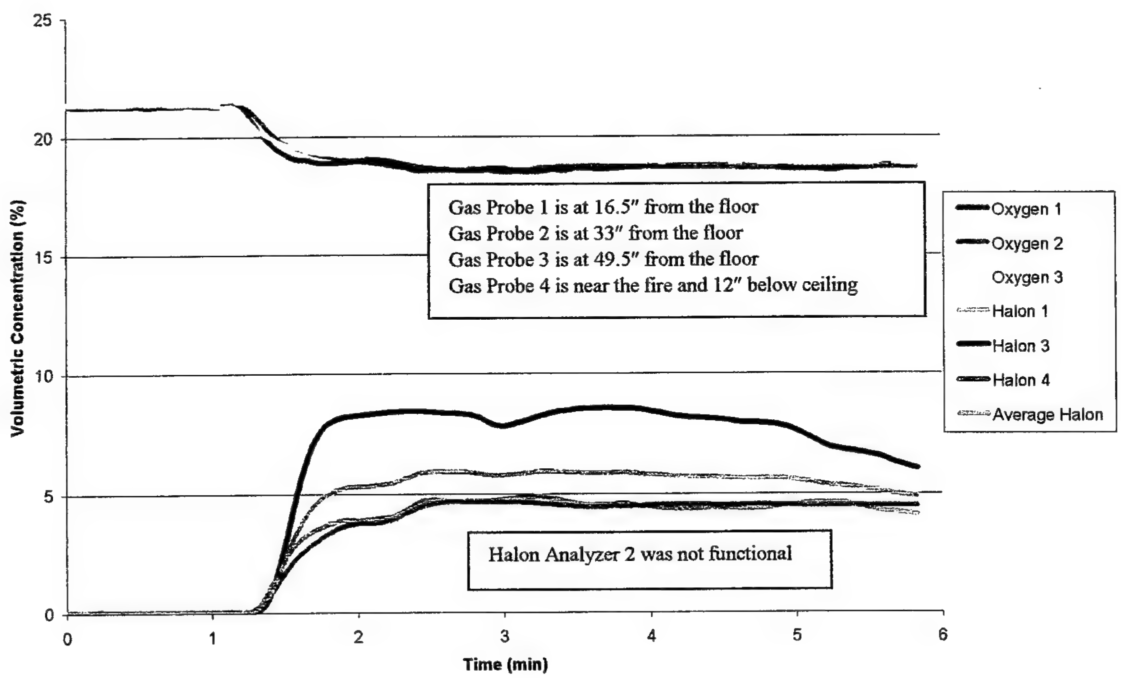


FIGURE 56. SURFACE BURN TEST 17 (111999T2) GAS CONCENTRATION PLOT

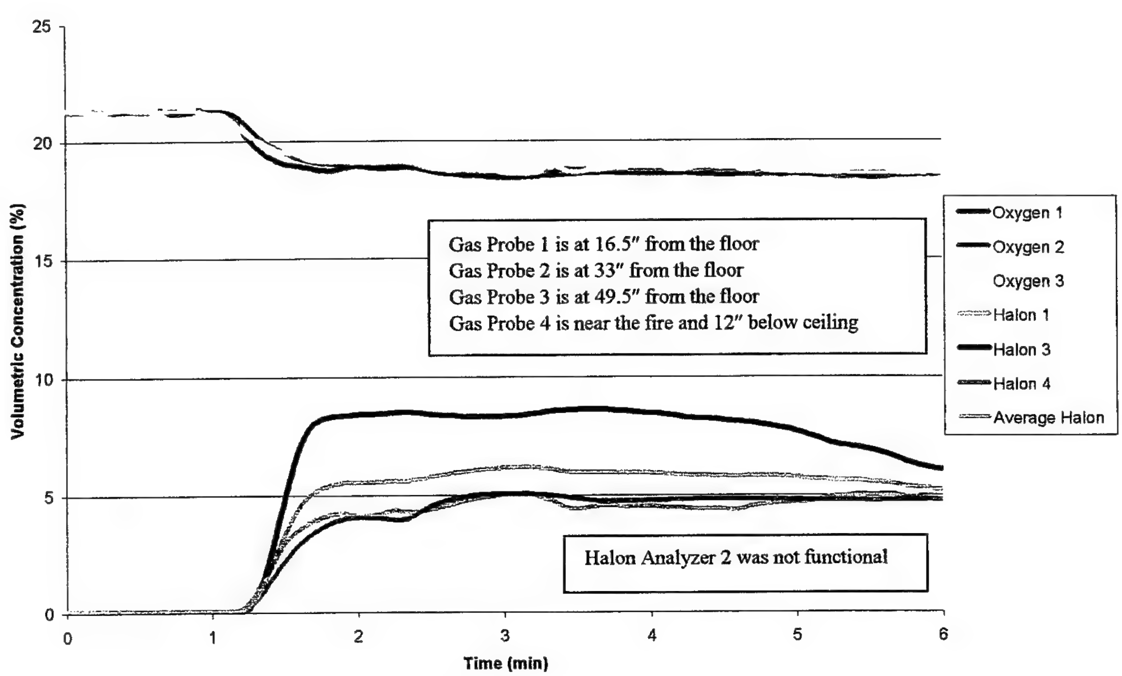


FIGURE 57. SURFACE BURN TEST 18 (111999T3) GAS CONCENTRATION PLOT

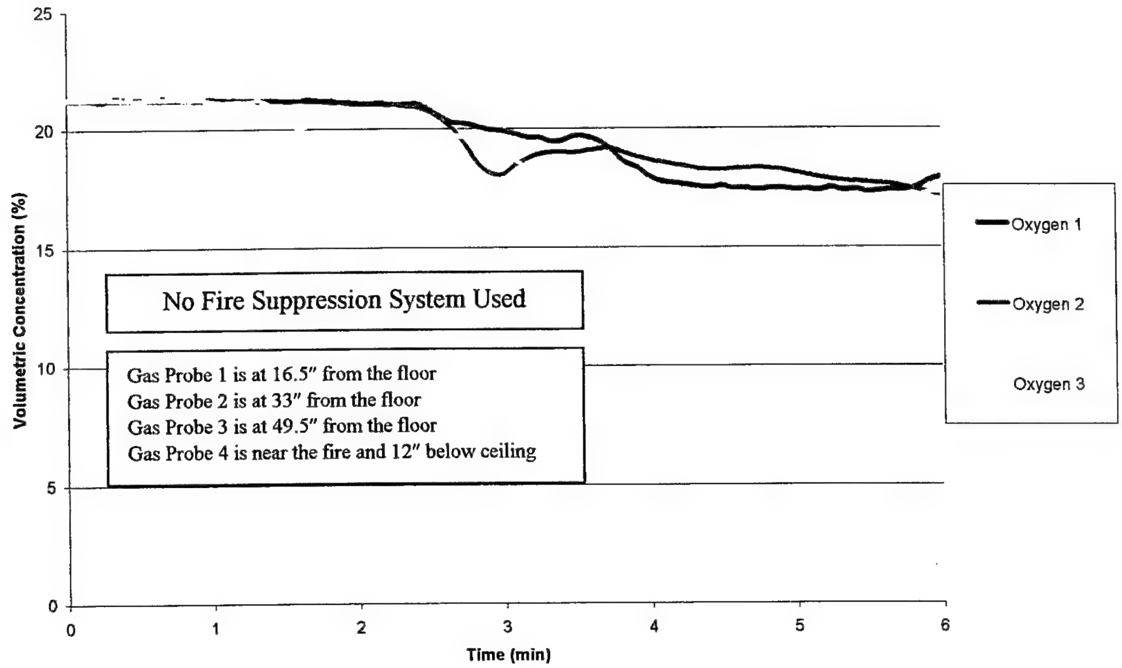


FIGURE 58. SURFACE BURN TEST 19 (111999T4) GAS CONCENTRATION PLOT

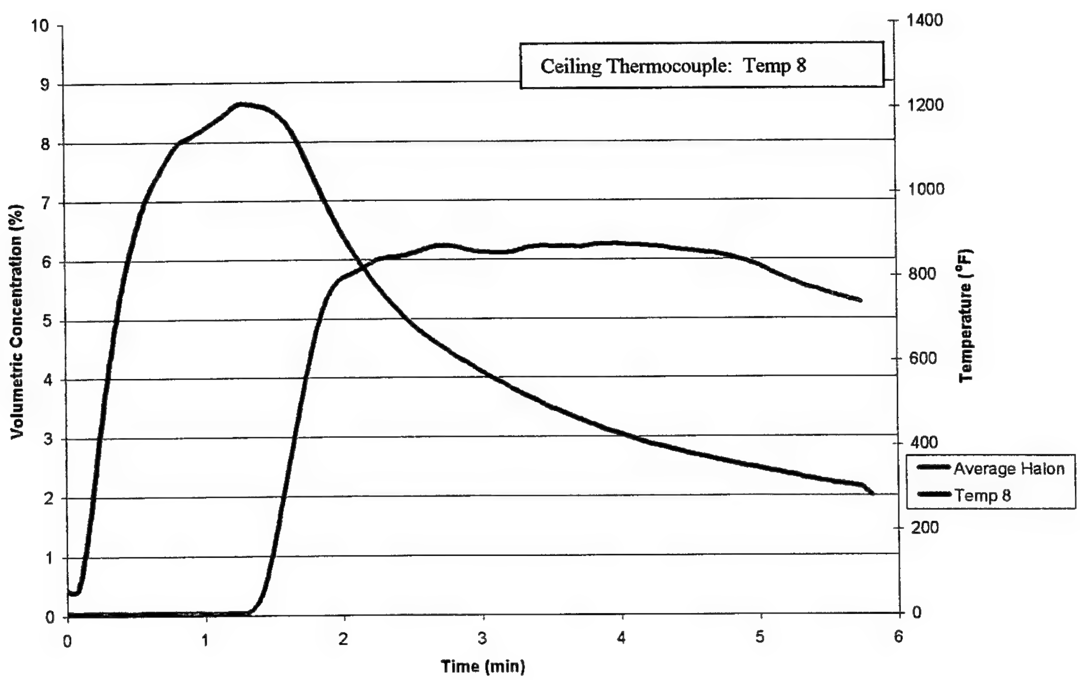


FIGURE 59. HALON 1301 VS TEMPERATURE DURING SURFACE BURN TEST 14 (111899T3)

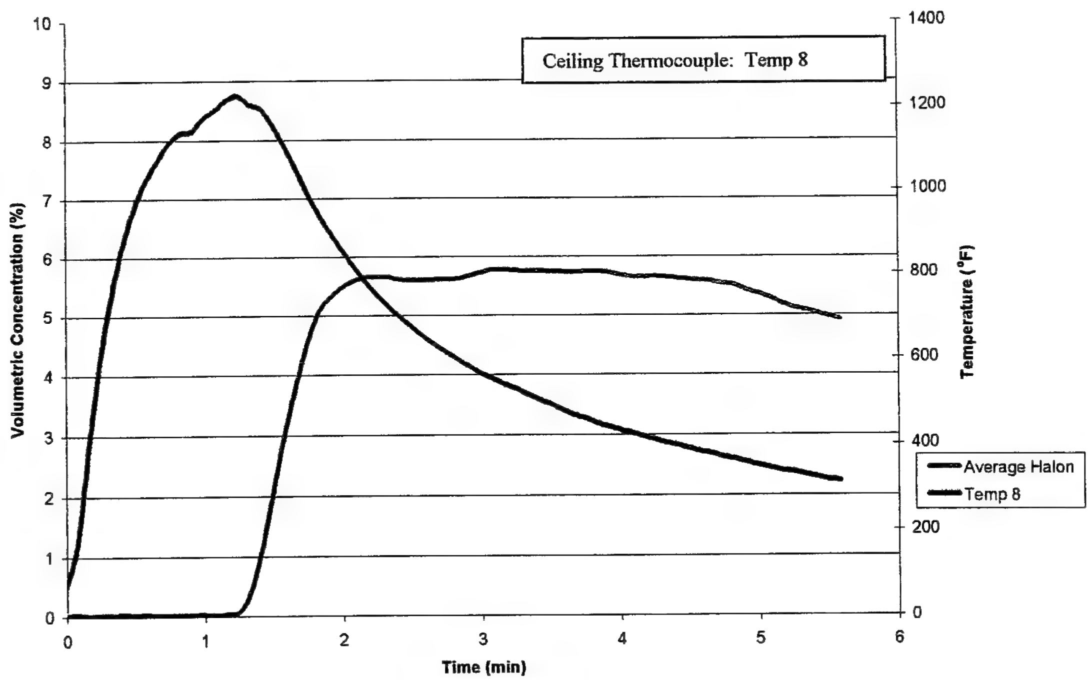


FIGURE 60. HALON 1301 VS TEMPERATURE DURING SURFACE BURN TEST 15 (111899T4)

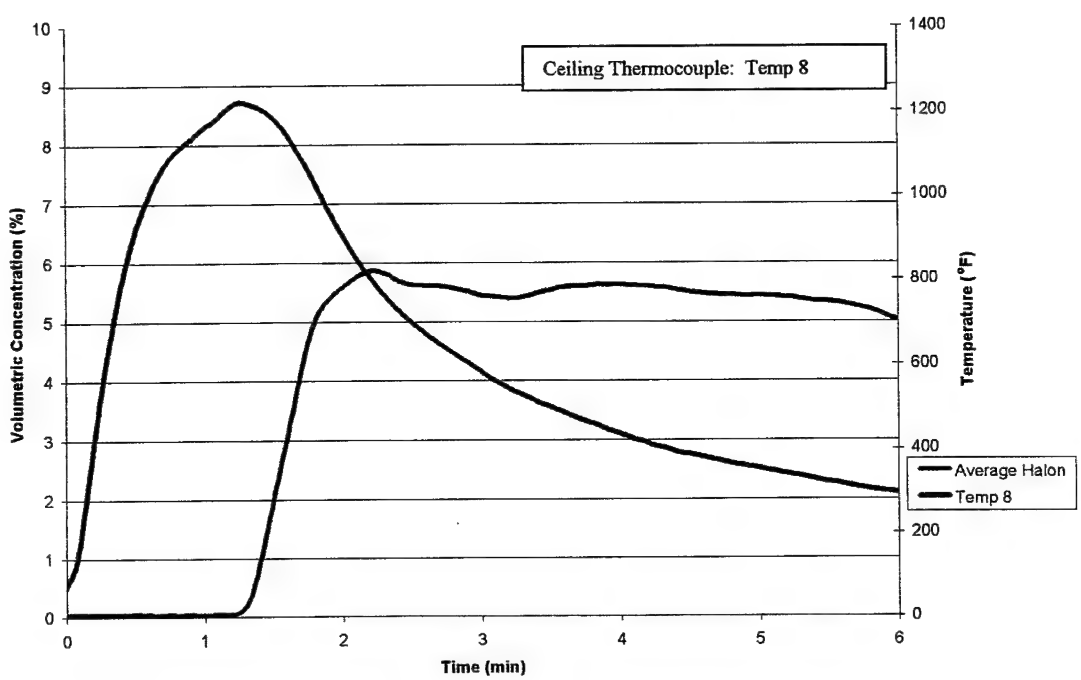


FIGURE 61. HALON 1301 VS TEMPERATURE DURING SURFACE BURN TEST 16 (111999T1)

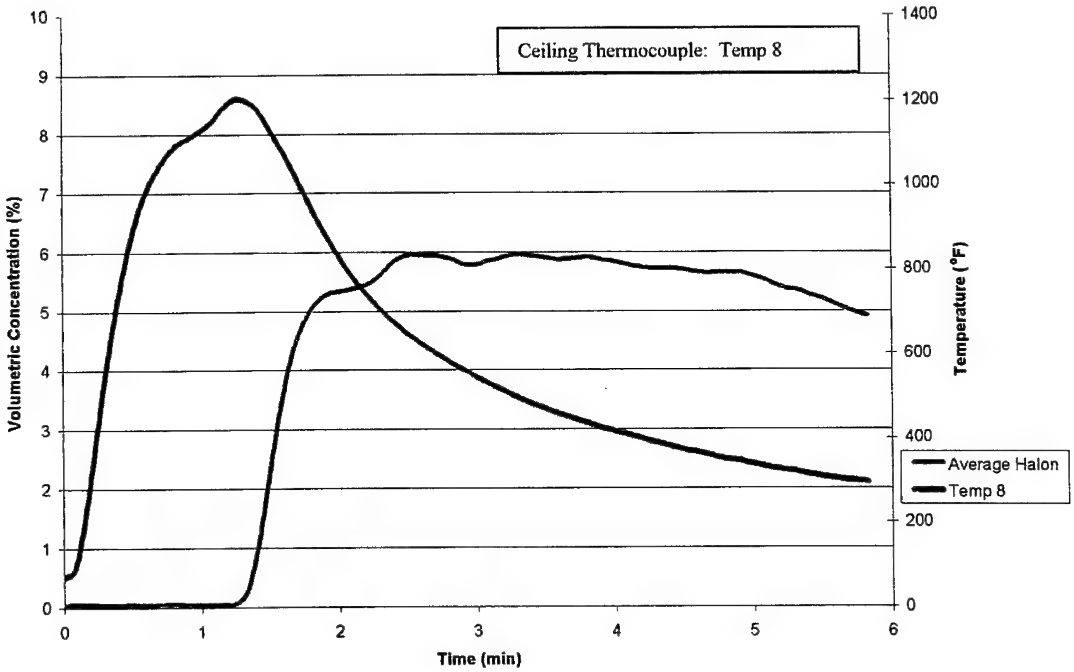


FIGURE 62. HALON 1301 VS TEMPERATURE DURING SURFACE BURN TEST 17 (111999T2)

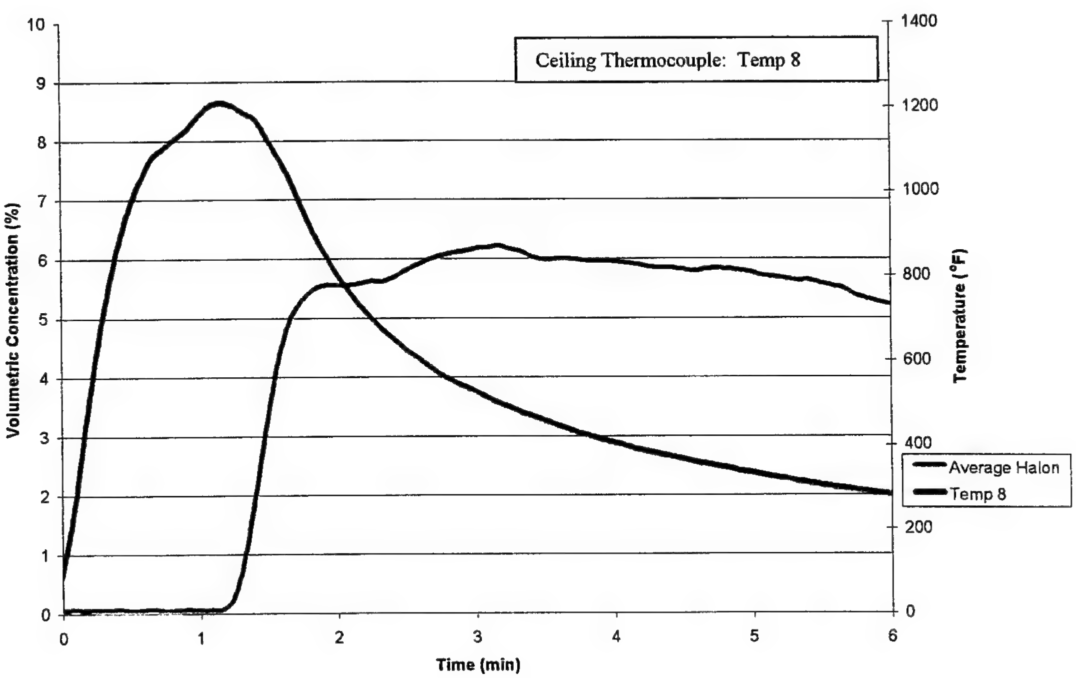


FIGURE 63. HALON 1301 VS TEMPERATURE DURING SURFACE BURN TEST 18 (111999T3)

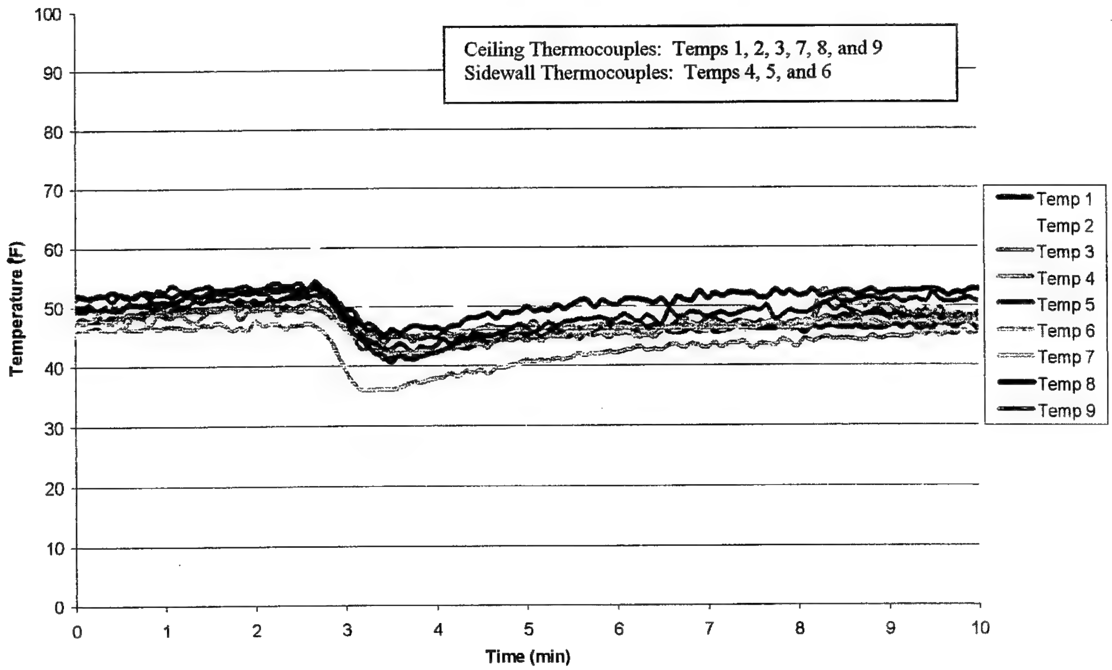


FIGURE 64. AEROSOL EXPLOSION TEST 25 (122199T1) TEMPERATURE PLOT

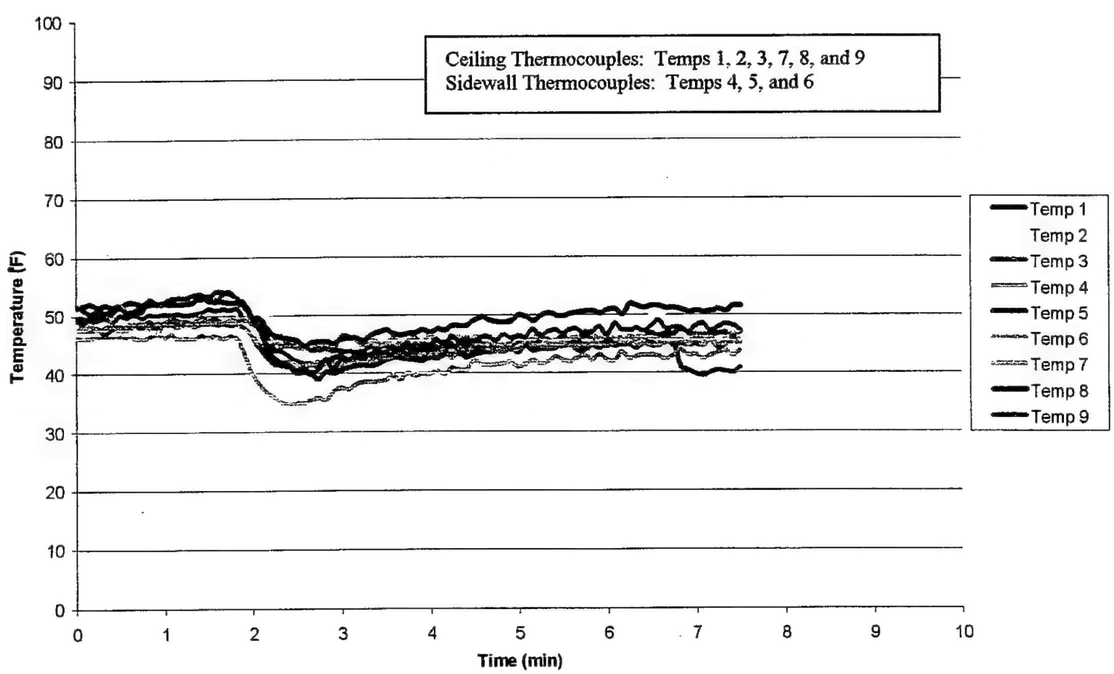


FIGURE 65. AEROSOL EXPLOSION TEST 26 (122199T3) TEMPERATURE PLOT

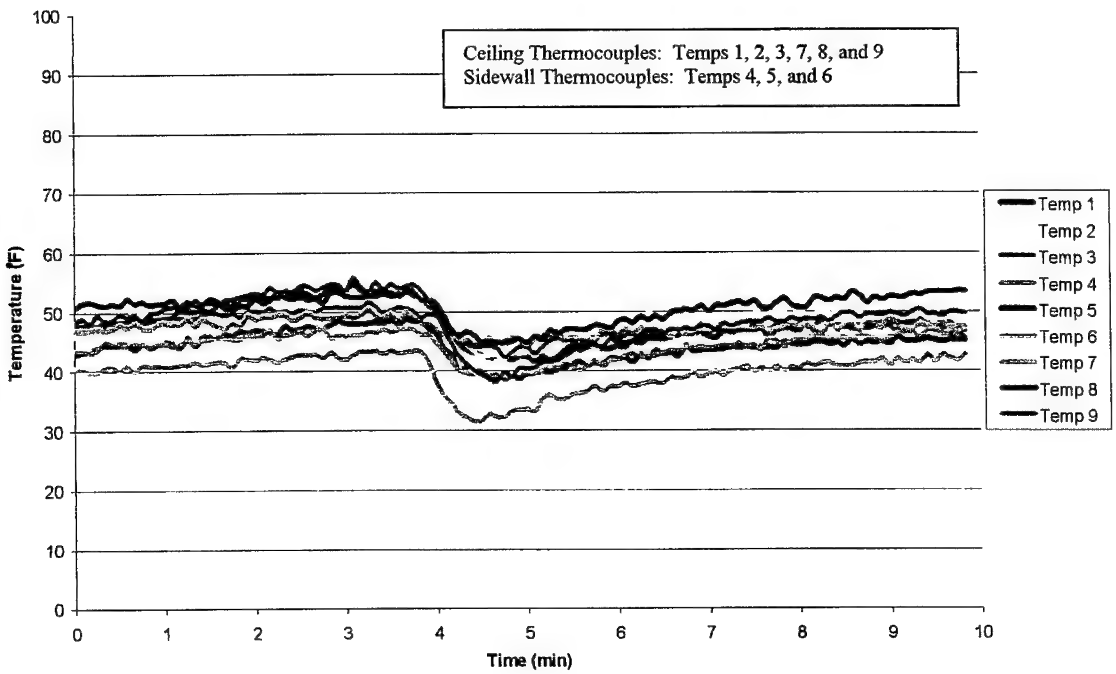


FIGURE 66. AEROSOL EXPLOSION TEST 27 (122299T1) TEMPERATURE PLOT

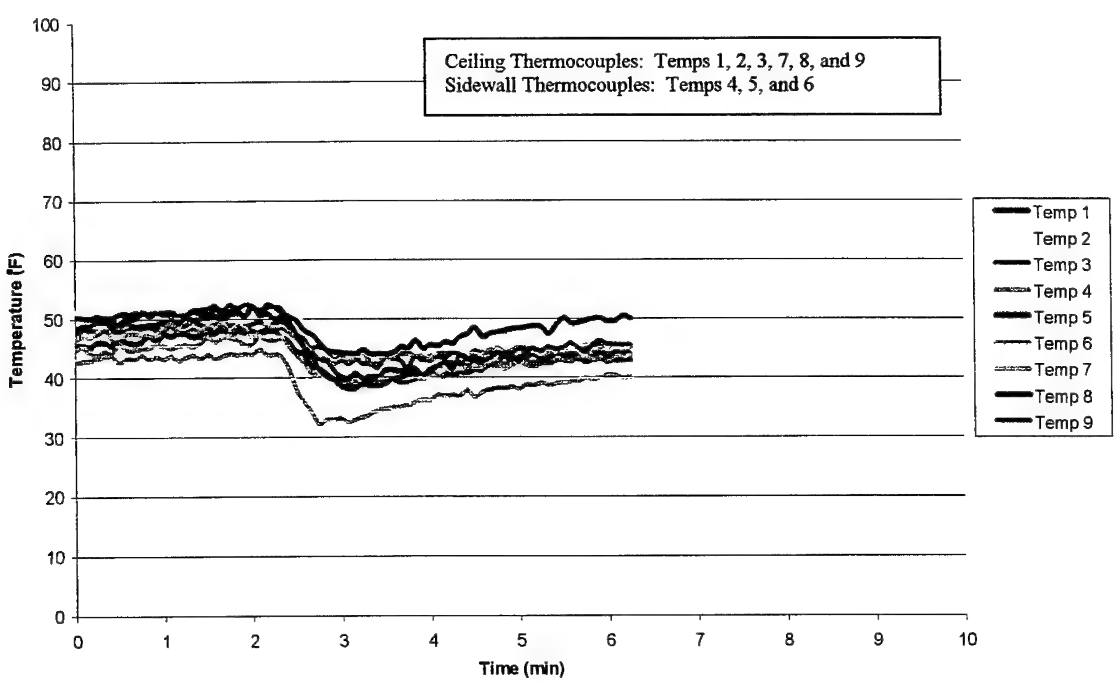


FIGURE 67. AEROSOL EXPLOSION TEST 28 (122299T2) TEMPERATURE PLOT

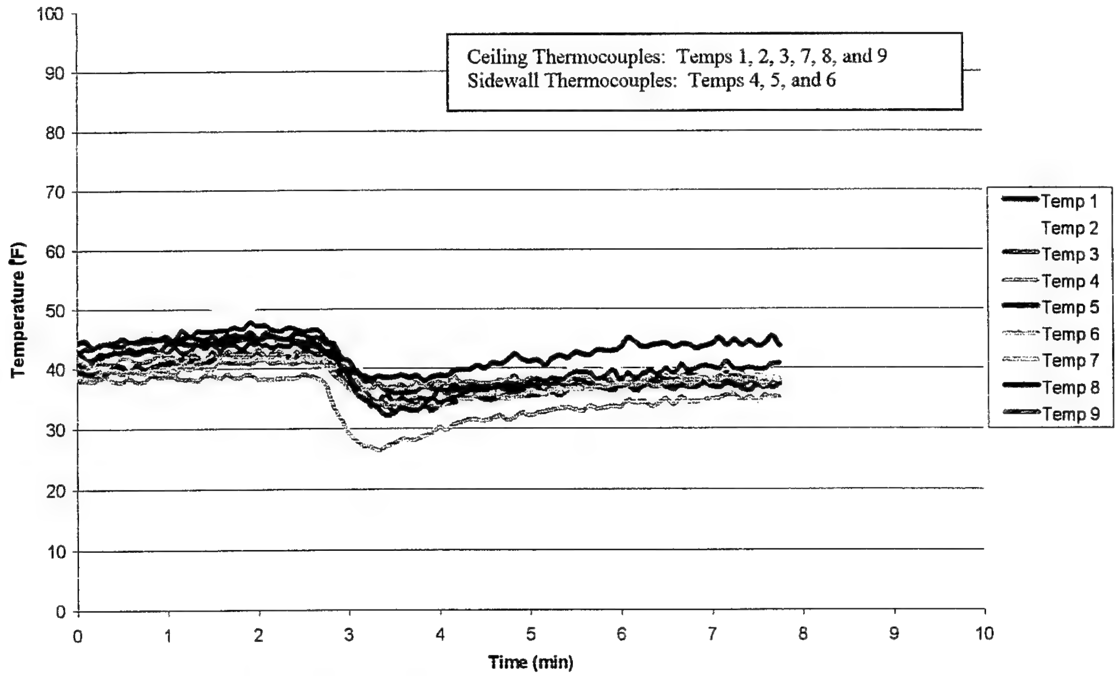


FIGURE 68. AEROSOL EXPLOSION TEST 29 (122299T3) TEMPERATURE PLOT

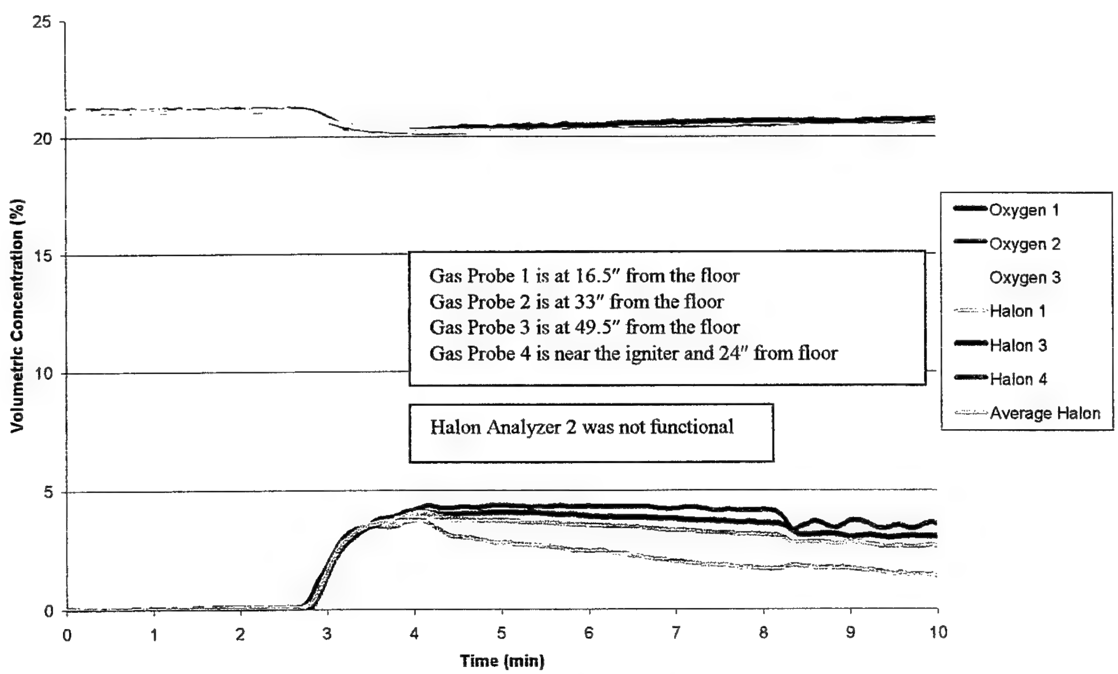


FIGURE 69. AEROSOL EXPLOSION TEST 25 (122199T1)
GAS CONCENTRATION PLOT

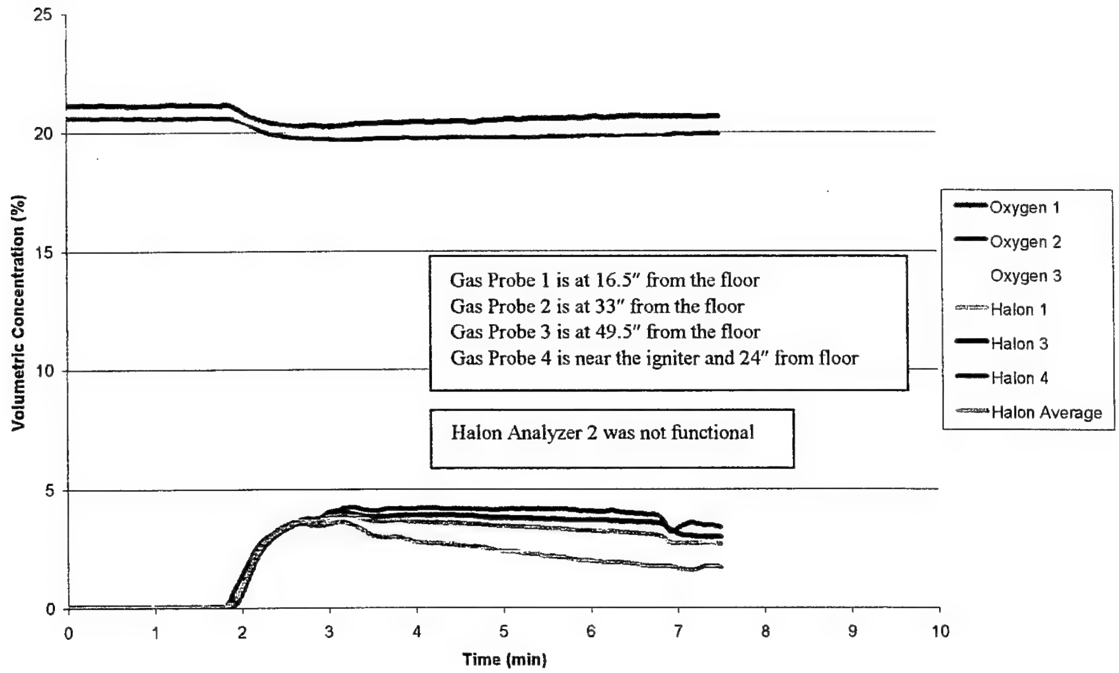


FIGURE 70. AEROSOL EXPLOSION TEST 26 (122199T3)
GAS CONCENTRATION PLOT

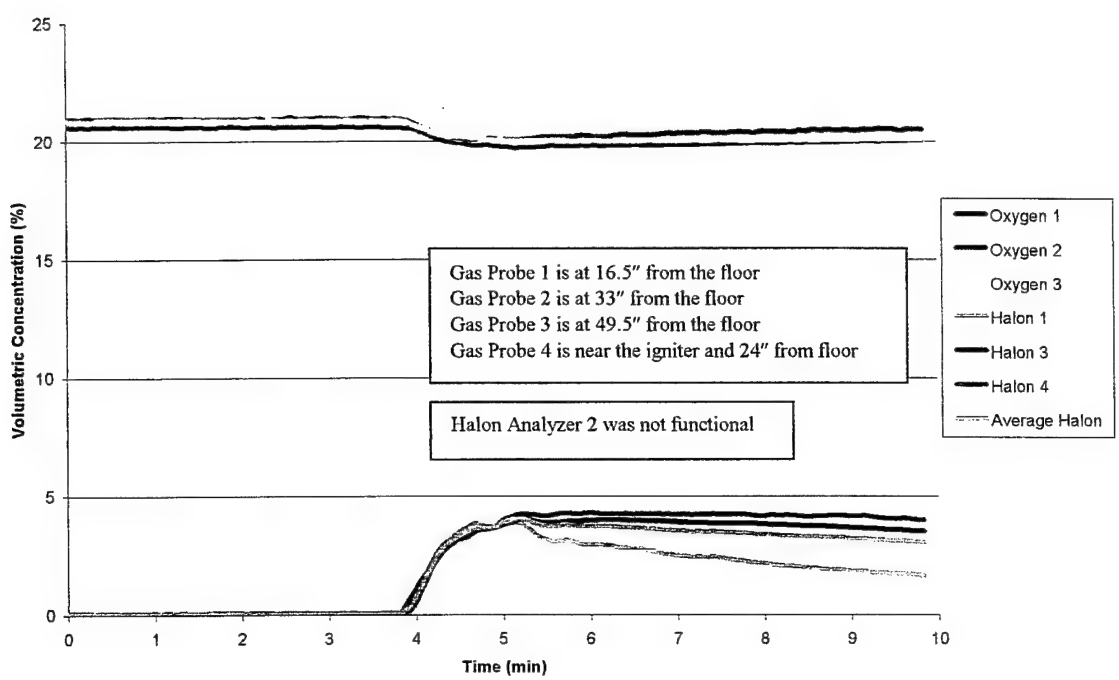


FIGURE 71. AEROSOL EXPLOSION TEST 27 (122299T1)
GAS CONCENTRATION PLOT

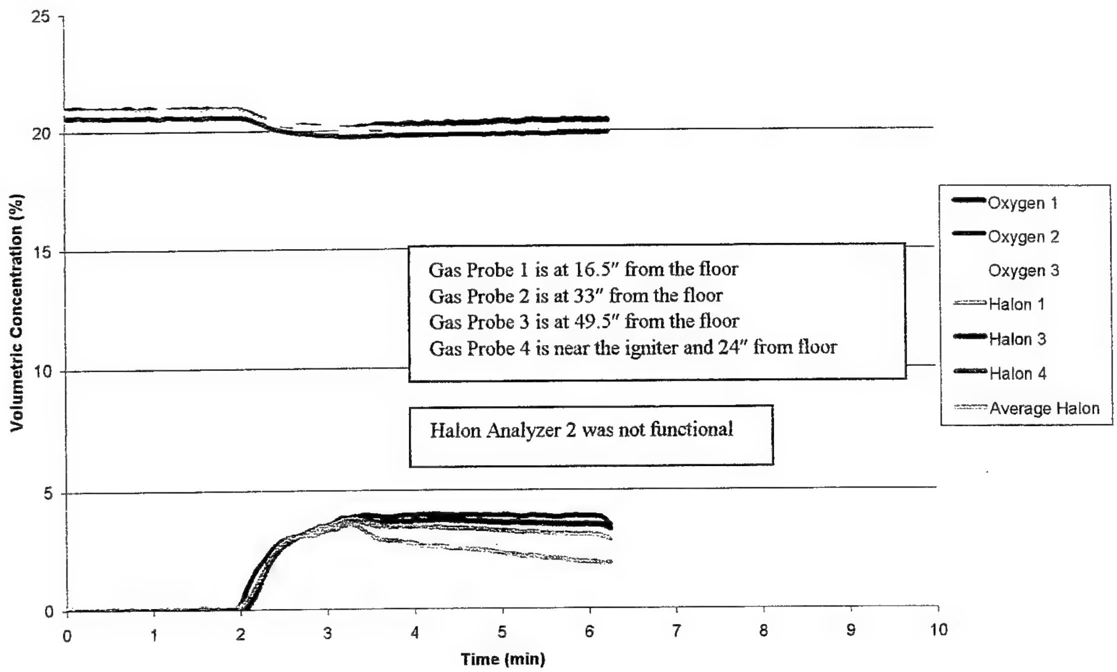


FIGURE 72. AEROSOL EXPLOSION TEST 28 (122299T2)
GAS CONCENTRATION PLOT

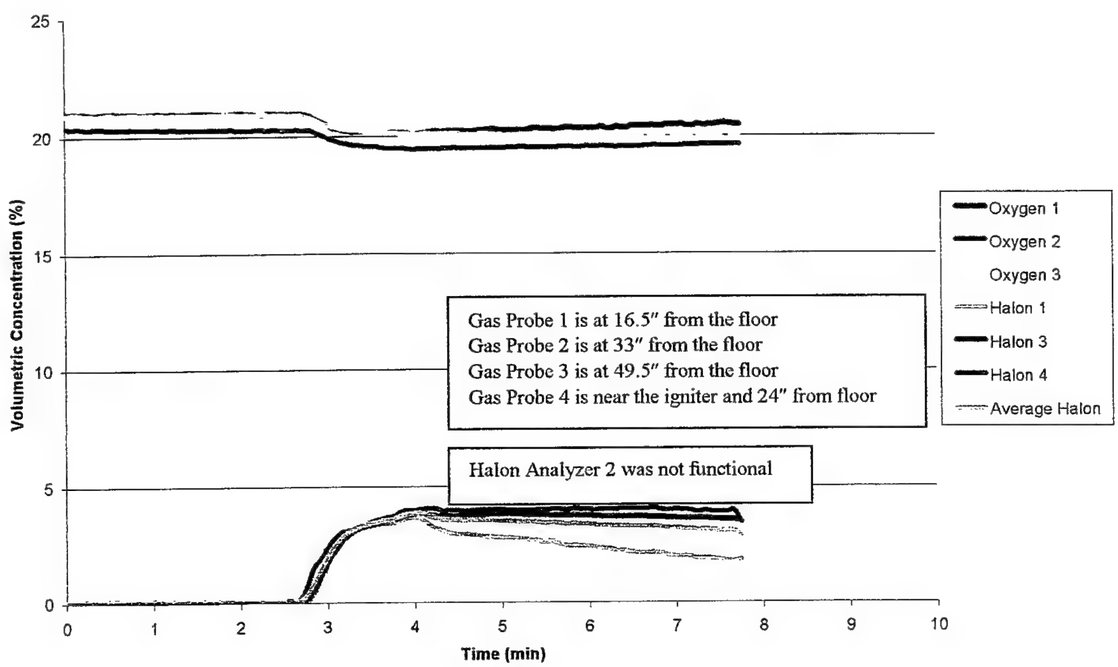


FIGURE 73. AEROSOL EXPLOSION TEST 29 (122299T3)
GAS CONCENTRATION PLOT

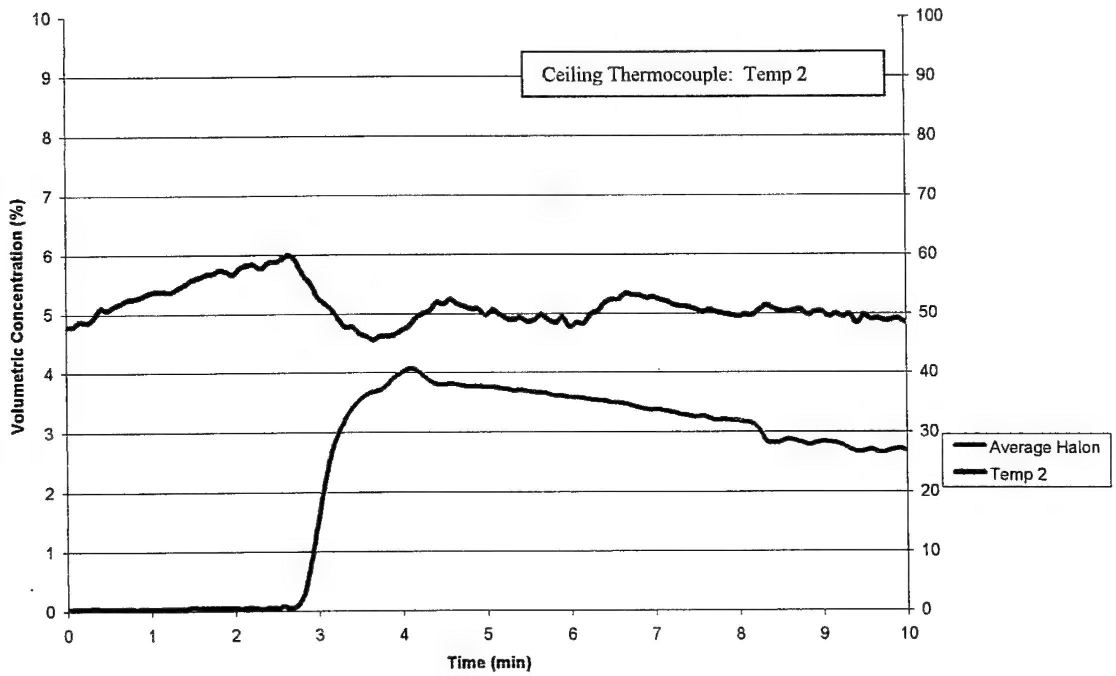


FIGURE 74. HALON 1301 VS TEMPERATURE DURING AEROSOL EXPLOSION TEST 25 (122199T1)

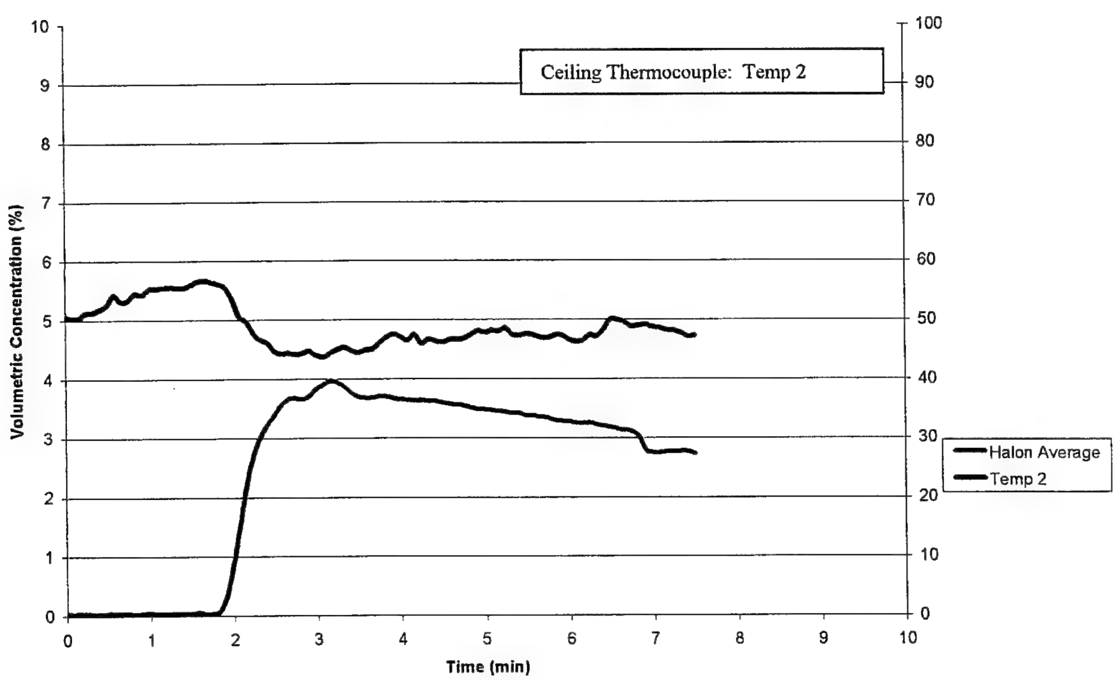


FIGURE 75. HALON 1301 VS TEMPERATURE DURING AEROSOL EXPLOSION TEST 26 (122199T3)

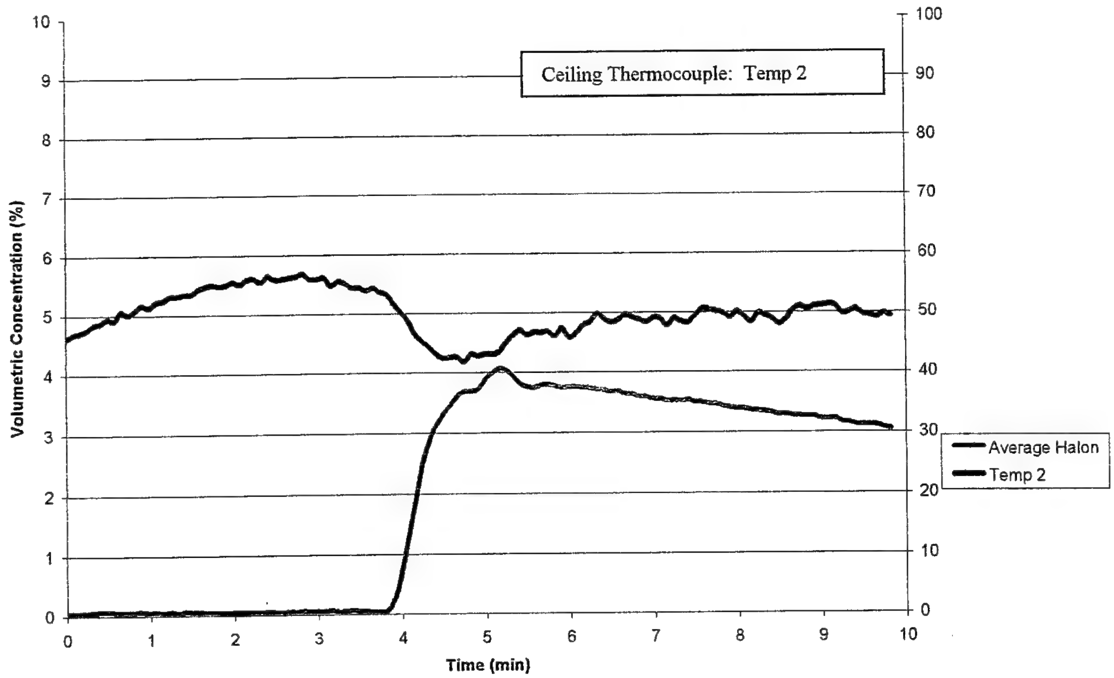


FIGURE 76. HALON 1301 VS TEMPERATURE DURING AEROSOL EXPLOSION TEST 27 (122299T1)

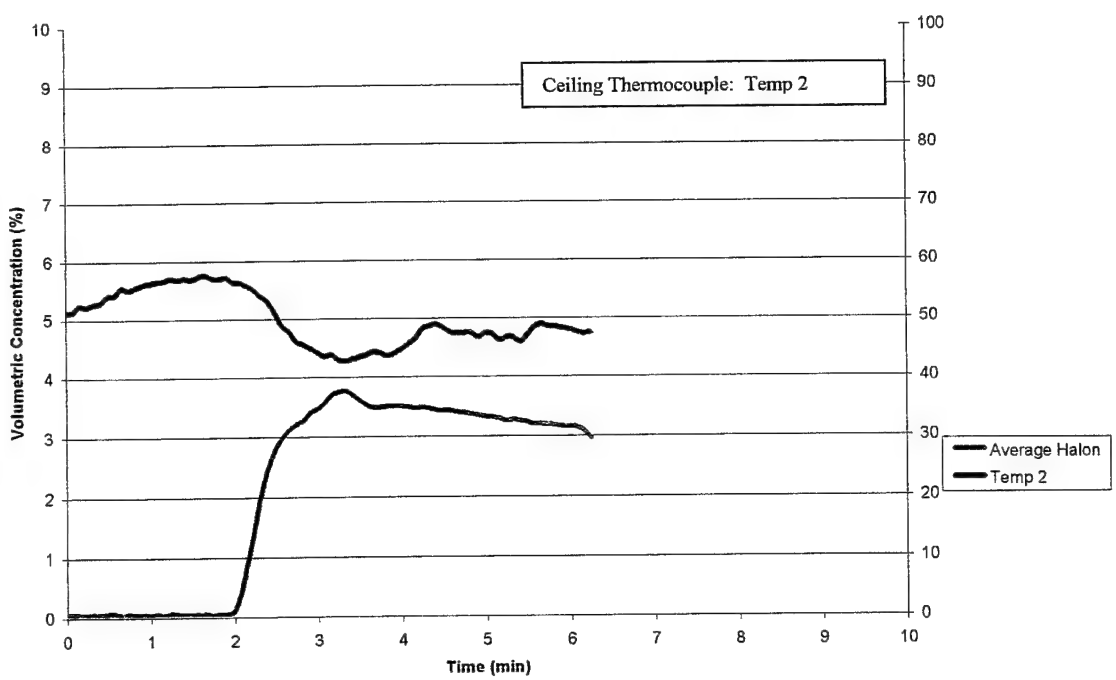


FIGURE 77. HALON 1301 VS TEMPERATURE DURING AEROSOL EXPLOSION TEST 28 (122299T2)

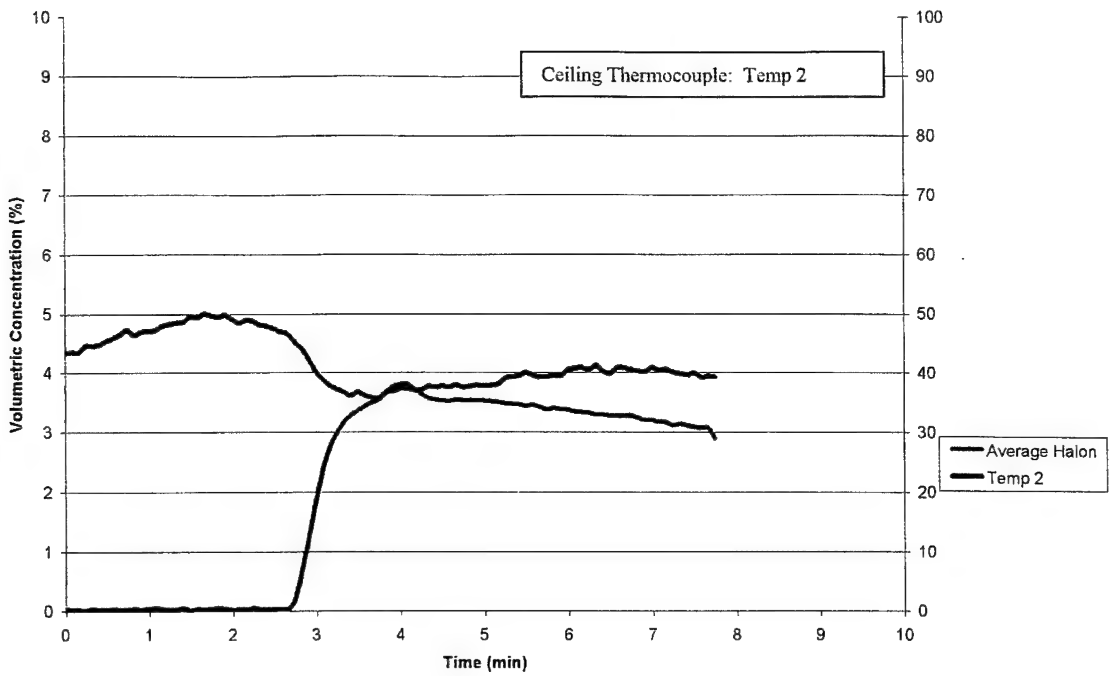


FIGURE 78. HALON 1301 VS TEMPERATURE DURING AEROSOL EXPLOSION TEST 29 (122299T3)

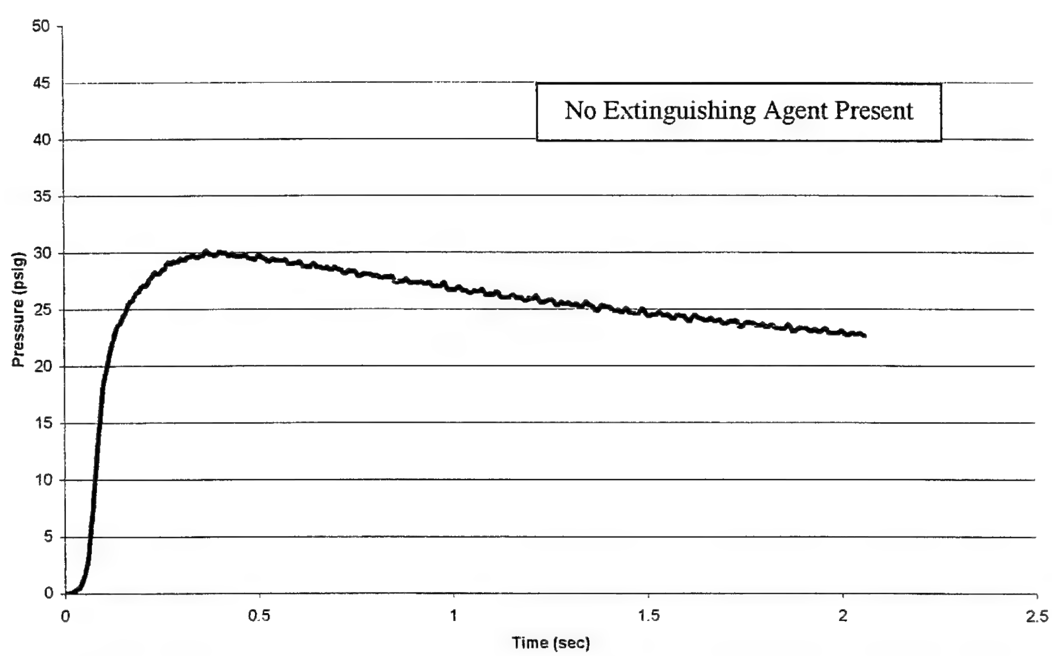


FIGURE 79. AEROSOL EXPLOSION TEST 20 (022599T6) PRESSURE PLOT

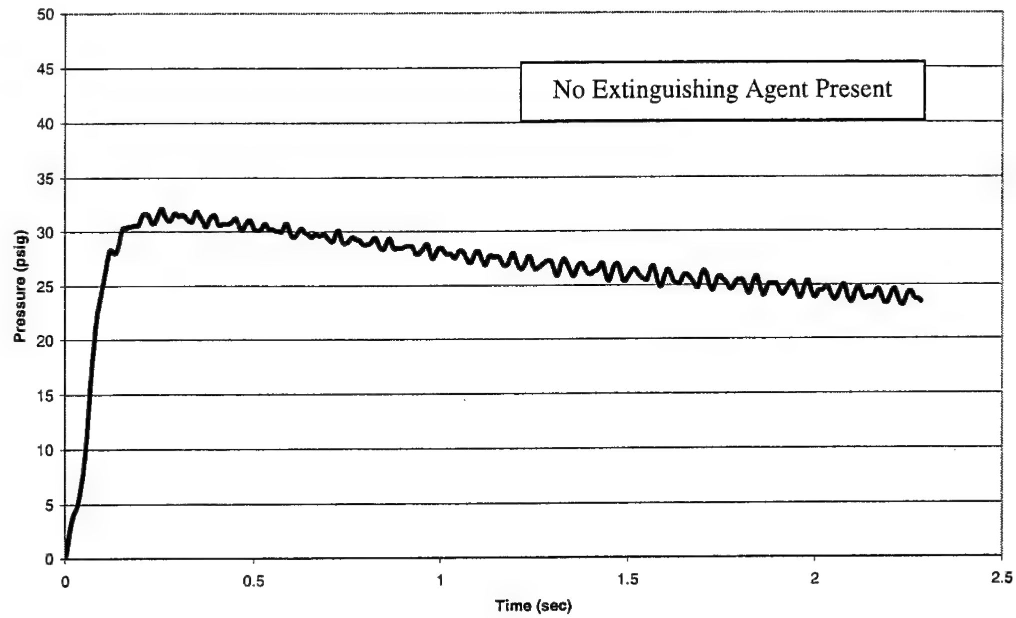


FIGURE 80. AEROSOL EXPLOSION TEST 21 (022599T7) PRESSURE PLOT

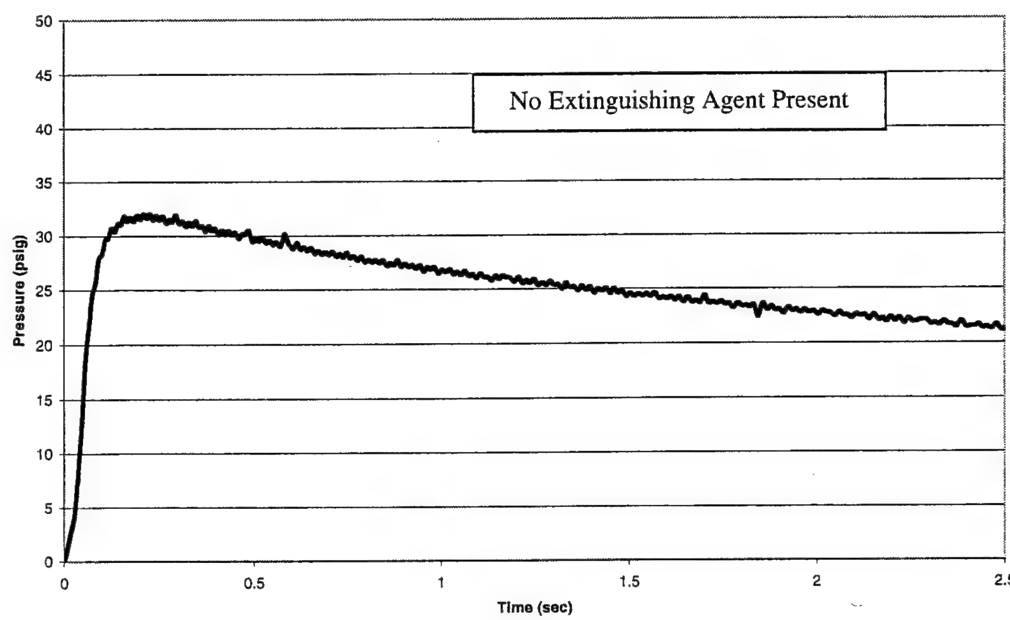


FIGURE 81. AEROSOL EXPLOSION TEST 22 (022599T8) PRESSURE PLOT

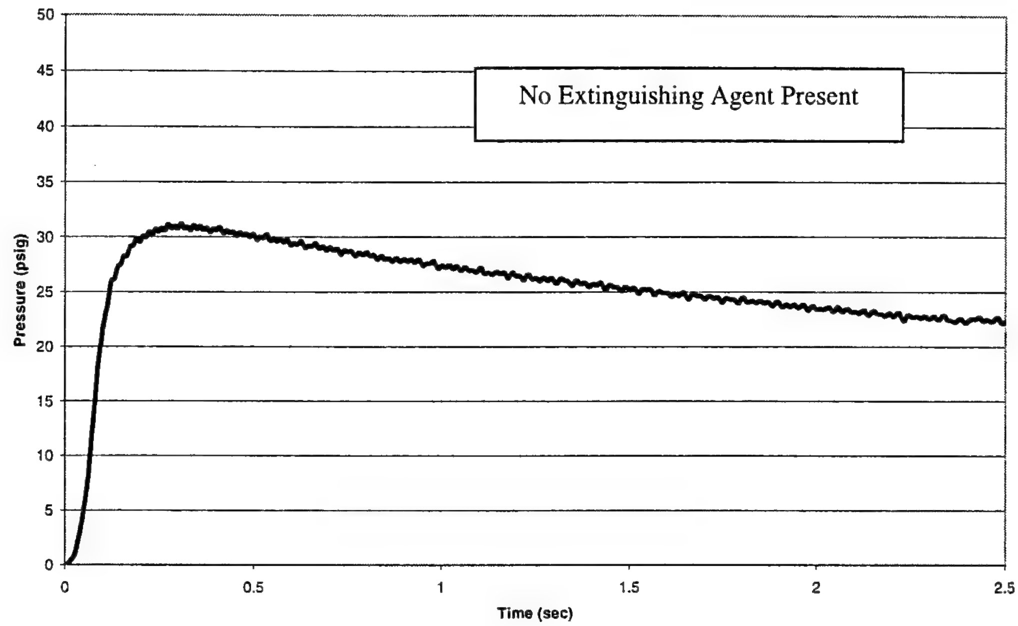


FIGURE 82. AEROSOL EXPLOSION TEST 23 (022599T9) PRESSURE PLOT

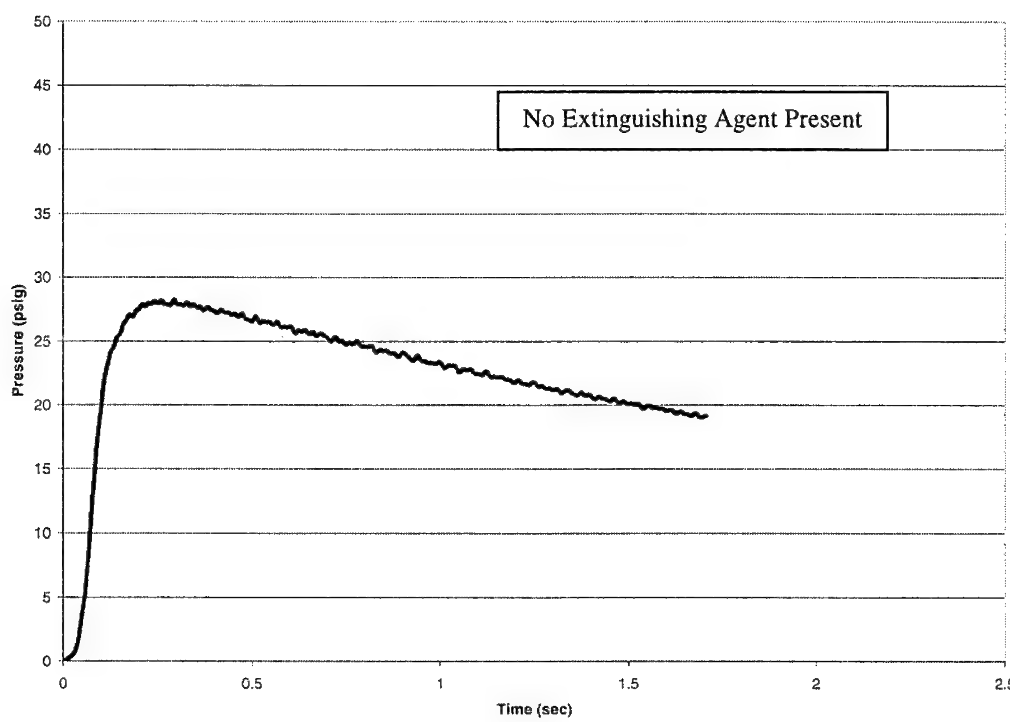


FIGURE 83. AEROSOL EXPLOSION TEST 24 (022599T10) PRESSURE PLOT

# APPENDIX A —MINIMUM PERFORMANCE STANDARDS FOR AIRCRAFT CARGO COMPARTMENT GASEOUS FIRE SUPPRESSION SYSTEMS

## A.1. INTRODUCTION.

Federal Aviation Regulations (FARs) and Joint Airworthiness Requirements (JARs) require fire suppression systems for some classifications of cargo compartments. In the past, the aircraft industry has selected Halon 1301 total flood fire suppression systems as the most effective systems for complying with the regulations. Because of the ban on production of Halon 1301, mandated by the Montreal Protocol and effective January 1994, new fire suppression systems will need to be certified when the use of Halon 1301 is no longer viable. The tests described in this standard are one part of the total FAA/JAA certification process for cargo compartment fire suppression systems. Compliance with other applicable regulations, some of which are listed below, is also required. Applicants attempting to certify replacement systems are encouraged to discuss the required process with regulatory agencies prior to conducting testing.

### A.1.1 APPLICABLE REGULATIONS.

The following existing FARs/JARs pertain to cargo compartment fire suppression systems:

§ 25.851 *[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-54, 45 FR 60173, Sep. 11, 1980; Amdt. 25-72, 55 FR 29783, Jul. 20, 1990; Amdt. 25-74, 56 FR 15456, Apr. 16, 1991]* "(b) Built-in fire extinguishers. If a built-in fire extinguisher is provided—

(1) Each built-in fire extinguishing system must be installed so that—

(i) No extinguishing agent likely to enter personnel compartments will be hazardous to the occupants; and

(ii) No discharge of the extinguisher can cause structural damage.

(2) The capacity of each required built-in extinguishing system must be adequate for any fire likely to occur in the compartment where used, considering the volume of the compartment and the ventilation rate."

§ 25.855 *[Doc. No. 5066, 29 FR 18291. Dec. 24, 1964, as amended by Amdt. 25-15, 32FR 13266, Sep. 20, 1967; Amdt. 25-32, 37 FR 3972, Feb. 24, 1972; Amdt. 25-60, 51 FR 18242, May 16, 1986; Amdt. 25-72, 55 FR 29784, Jul. 20, 1990; Amdt. 25-93, 63 FR 8048, Feb. 17, 1998]* "(h) Flight tests must be conducted to show compliance with the provisions of Sec. 25.857 concerning—

(1) Compartment accessibility,

(2) The entries of hazardous quantities of smoke or extinguishing agent into compartments occupied by the crew or passengers, and

(3) The dissipation of the extinguishing agent in Class C compartments.

(i) During the above tests, it must be shown that no inadvertent operation of smoke or fire detectors in any compartment would occur as a result of fire contained in any other compartment, either during or after extinguishment, unless the extinguishing system floods each such compartment simultaneously."

§ 25.857 *[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-32, 37 FR 3972, Feb. 24, 1972; Amdt. 25-60, 51 FR 18243, May 16, 1986; Amdt. 25-93, 63 FR 8048, Feb. 17, 1998]* "(c) Class C. A Class C cargo compartment is one not meeting the requirements for either a Class A or Class B compartment but in which—

(1) There is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station.

(2) There is an approved built-in fire extinguishing or suppression system controllable from the cockpit;

(3) There are means to exclude hazardous quantities of smoke, flames, or extinguishing agent, from any compartment occupied by the crew or passengers;

(4) There are means to control ventilation and drafts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment."

In addition to these regulations, the FAA issued Airworthiness Directive 93-07-15 which required, among other things, that after November 2, 1996, the Class B cargo compartments on Boeing Models 707, 727, 737, 747, and 757 and McDonnell Douglas Models DC-8, DC-9, and DC-10 Series airplanes have improved fire protection features. One of three options available to comply with this AD is to modify Class B cargo compartments on these airplanes to comply with the requirements for Class C compartments. This option would require the installation of a fire suppression system.

One other area of rulemaking activity relating to cargo compartment suppression system requirements is the "Revised Standards for Cargo or Baggage Compartments in Transport Category Airplanes, Final Rule," amendments 25-97, and amendments 121-269, effective March 19, 1998. This rule eliminates Class D cargo compartments on newly certified aircraft under Part 25 and requires existing Class D compartments on Part 121 certified passenger aircraft to comply with the detection and suppression/extinguishing system aspects of Class C cargo compartment requirements by March 19, 2001. This rule was issued by the FAA and at this time applies only to aircraft operated by U.S.-based airlines.

## A.2. SCOPE.

This document establishes the minimum performance standards (MPS) that a cargo compartment fire suppression system must meet. It describes the tests that should be performed to demonstrate that the performance of the replacement agent/systems equals the performance of the currently approved Halon 1301 systems.

## A.3. AGENT SELECTION GUIDANCE.

### A.3.1 ENVIRONMENTAL.

The replacement agent must be approved under the Environmental Protection Agency (EPA), Clean Air Act, Significant New Alternatives Policy (SNAP) program, or other international governmental approving program. The primary environmental characteristics to be considered in assessing a new agent are Ozone Depletion Potential (ODP), Global Warming Potential (GWP), and Atmospheric Lifetime. The agent selected should have environmental characteristics in harmony with international laws and agreements, as well as applicable local laws. This MPS sets out the means of assessing the technical performance of potential alternatives. In selecting a new agent, it should be noted that an agent which does not have a zero or near zero ODP and the lowest practical GWP and Atmospheric Lifetime may have problems of international availability and commercial longevity.

### A.3.2 TOXICOLOGY.

The toxicological acceptability of an agent is dependent on its use pattern. As a general rule, the agent must not pose an unacceptable health hazard for workers during installation and maintenance of the suppression system. At no time should the concentration present an unacceptable health hazard in areas where passengers or workers are present or where leakage could cause an agent to enter an occupied area. Following the release of the agent during fire suppression, the cumulative effect of the agent, its pyrolytic breakdown products, and the by-products of combustion must not pose an unacceptable health hazard.

FAR Parts 25.851, 25.855, and 25.857 all address the issue of hazardous quantities of smoke, gas, or extinguishing agent in occupied compartments. Conducting the fire tests described in this MPS does not address those issues. The FAA William J. Hughes Technical Center has conducted tests in an aircraft fuselage with in-flight airflow conditions. Data on the level of smoke, gases, and extinguishing agent in the normally occupied sections of the fuselage are available for some suppression agents and systems.

## A.4. TEST REQUIREMENTS.

### A.4.1 TEST ARTICLE.

The fire tests are to be conducted inside a simulated below floor cargo compartment of a wide-body aircraft. The volume of the compartment should be 2000 ± 100 cubic feet (56.6 ± 2.8 $m^3$) as shown in figure A-1. The leakage rate from the compartment should be 50 ± 5 cubic feet per minute (1.4 ± 0.14 cubic meter per minute). The leakage from the compartment should be configured to simulate the "U" shape of the cargo door seals that would exist on an actual aircraft. This can be done by installing perforated ducts inside the compartment in the shape of the perimeter of a cargo door and then venting those ducts outside the test article. A variable speed fan installed in the exit of the duct should be used to draw air out of the compartment. One-inch-diameter holes spaced at one hole every 5 inches (12.7 cm) in a round, 4-inch-diameter-steel duct has been shown to be effective. The perforated ducts should be installed on

the opposite side of the cargo compartment from where the ignited box for the bulk-load and containerized-load fire scenarios are located. The return air back into the compartment should be evenly distributed and not from any one location.

### A.4.2 INSTRUMENTATION.

Temperature measurements should be taken throughout the cargo compartment. The compartment shall be monitored with Type K chromel/alumel 22 gauge thermocouples (exposed); the loop to be formed by the thermocouple junction (bead) shall be 0.044 ± 0.010 inch (1.12 mm ± 0.254 mm) in diameter. Ceiling thermocouples should be evenly spaced along the compartment ceiling with a maximum of 5 feet between adjacent thermocouples. One of the ceiling thermocouples should be installed directly above the initial ignition location for all fire scenarios. The beads of the ceiling thermocouples shall be 1 inch (2.5 cm) below the compartment ceiling. At least one thermocouple should be placed on the compartment sidewall 1 foot below ceiling level and centered on the fire ignition location. The sidewall thermocouple should be installed on the side of the compartment nearest the ignition location. At least two additional thermocouples should be placed in and above the box containing the igniter for the bulk and containerized fire scenarios. The purpose of these two thermocouples is to monitor and verify the ignition of the boxes. The readings are not part of the acceptance criteria. Care should be taken to prevent these thermocouples from contacting the energized coil of nichrome wire.

A continuous gas analyzer with a real time display of the gas (extinguishing agent) volumetric concentration is required for the aerosol can scenario when the suppression system is a gaseous total flood system. A continuous gas analyzer may be required, depending on the suppression system design, for the bulk-load and containerized-load scenarios. Section A.4.4 describes the conditions when this may occur. The accuracy of the analyzer shall be ± 5% of the reading. The gas analyzer is used to measure the concentration of the gaseous suppression agent. The data-sampling rate for all the temperature measurements and the gas concentrations should be at least one data point every 5 seconds.

A pressure transducer is also required for the aerosol can fire scenario. The response time of the transducer should be 0.02 seconds or faster. Omega® manufactures several transducers suitable for this application. The transducer should be mounted on the ceiling in the geometric center of the compartment. The data-sampling rate for the pressure transducer should be at least 50 data points per second.

### A.4.3 FIRE SCENARIOS.

The aircraft cargo compartment fire suppression system must successfully control the following four different fire scenarios.

#### A.4.3.1 Bulk Fire Load.

The fire load for this scenario shall be single-wall corrugated cardboard boxes, with nominal dimensions of 18 × 18 × 18 inches (45.7 × 45.7 × 45.7 cm). The weight per unit area of the cardboard should be 0.11 lbs/ft$^2$ (0.5417 kg/m$^2$). The boxes should be filled with 2.5 pounds

(1.1 kg) of shredded office paper, loosely packed without compacting. The weight of the filled box should be 4.5 ± 0.4 lbs. (2.0 ± 0.2 kg). The flaps of the boxes should be tucked under each other with no staples or tape used. The boxes should be stacked in two layers into the cargo compartment in a quantity representing 30% of the cargo compartment empty volume. For a 2000 cubic foot (56.6 $m^3$) compartment, this would require 178 boxes. The boxes shall be touching each other without any significant air gaps between boxes. The test fire is ignited by applying 115 VAC to a 7 foot (2.1 m) length of nichrome wire. The wire is wrapped around four folded (in half) paper towels. The resistance of the nichrome igniter coil should be approximately 7 ohms. The igniter should be placed into the center of a box on the bottom outside row of the stacked boxes. Several ventilation holes should be placed in the side of the box to ensure that the fire does not self extinguish. Ten, 1.0-inch (2.5-cm) -diameter holes have been shown to be effective. See figures A-2 and A-3.

A.4.3.2 Containerized Fire Load.

The same type of cardboard boxes filled with shredded office paper and the same igniter used in the bulk-load fire scenario should be used in this scenario. The boxes should be stacked inside an LD-3 container as shown in figure A-4. The boxes shall be touching each other with no significant air gaps between them. The container shall be constructed of an aluminum top and inboard side, a Lexan (polycarbonate) front, and the remainder of steel. Two rectangular slots for ventilation should be cut into the container in the center of the Lexan front and in the center of the sloping sidewall. The slots should be 12 by 3 ± 1/4 inch (30.5 × 7.6 ± 0.6 cm). See figure A-5. The igniter is placed in a box on the bottom row, in the corner nearest the sloping side of the container and the Lexan. Ventilation holes should be placed in the sides of the box. Ten, 1.0-inch (2.5-cm) -diameter holes have been shown to be effective. Two additional, empty LD-3 containers are placed adjacent to the first container. See figure A-6.

A.4.3.3 Surface Burning Fire.

One-half U.S. gallon (1.9 liters) of Jet A fuel in a square pan should be used for this scenario. The pan should be constructed of 1/8-inch (0.3-cm) steel and measure 2 feet by 2 feet by 4 inches high (60.9 cm × 60.9 cm × 10.2 cm). Approximately 13 fluid ounces (385 ml.) of gasoline should be added to the pan to make ignition easier. Two and one-half gallons (9.5 liters) of water placed in the pan has been found to be useful in keeping the pan cooler and minimizing warping. This quantity of fuel and pan size is sufficient to burn vigorously for approximately 4 minutes if not suppressed. The position of the pan in the cargo compartment should be in the most difficult location for the particular suppression system being tested. The pan should be located 12 inches below the cargo compartment ceiling if the suppression system uses a gaseous agent with a density at standard pressure and temperature (14.7 psia (101.3 kPa), 59.0°F (15°C)) greater than air. The pan should be 12 inches (30.5 cm) above the floor of the compartment if the suppression system uses a gaseous agent with a density less than air at standard pressure and temperature. The pan should be at the compartment mid height when the suppression agent has a density equal to that of air. The pan should be located at the maximum horizontal distance from any discharge nozzles for all tests, regardless of the suppression agent used. See figure A-7.

A.4.3.4 Exploding Aerosol Can Fire.

This scenario addresses the overpressure and bursting of an aerosol can involved in a cargo fire and the potential for the ignition of the released hydrocarbon propellant used in these cans. The FAA William J. Hughes Technical Center has developed an aerosol can simulator that releases a mixture of propane and alcohol through a large area valve and across sparking electrodes.

The aerosol explosion simulator must utilize a cylindrical pressure vessel for the storage of flammable base product and propellant. The pressure vessel must be capable of withstanding a minimum pressure of 300 psi (2068.5 KPa). The pressure vessel must be mated to a ball valve capable of withstanding a minimum pressure of 300 psi (2068.5 KPa). The port diameter of the ball must be 1.5 inches (3.8 cm) (note: a ball valve is typically classified according to the diameter of the pipe that it connects to, but this is not necessarily the size of the ball port). The ball valve must be capable of rotating from the fully closed position to the fully open position in less than 0.1 second to allow the formation of a vapor cloud. Longer opening durations will significantly affect the vapor cloud formation and, hence, the explosive force yielded. The ball valve can be activated by any suitable means, including pneumatic or hydraulic actuators or manually via the appropriate linkage. The pressure vessel must be mounted vertically above the ball valve to allow for complete expulsion of the liquid contents. A discharge elbow located vertically under the ball valve will direct the contents horizontally (figure A-8).

Pressure Vessel. A steel 2-inch (5.1-cm) diameter, 11-inch (27.9-cm) -long schedule 80 pipe welded or capped at one end has been found suitable for storage of the pressurized mix.

Ball Valve. The 2-inch (5.1-cm) valve must be constructed of a material capable of withstanding interaction with ethanol and propane. A DynaQuip® stainless steel valve has been found suitable for this application.

Ball-Valve Actuator. A pneumatic rotary actuator has been found suitable for quickly and reliably rotating the ball valve from closed to fully open. A Speedaire® 90-degree actuator with a 2-inch (5.1-cm) bore performs well.

Propellant Heater. A system for heating the pressurized propellant mix after transfer to the pressure vessel must be provided. This would include a hot-air gun directed toward the pressure vessel, a hot-wire wrap, or other suitable means.

Pressure Gauge. A suitable device for measuring the pressure of the contents must be installed on the simulator pressure vessel. The device must be capable of measuring the pressure to within $\pm$ 5 psi (34.5 KPa).

Propellant Mix. The base product/propellant mix should consist of 20% liquid propane ($C_3H_8$, 3.2 ounces [0.09 kg]), 60% ethanol (denatured alcohol, 9.6 ounces [0.27 kg]), and 20% water (3.2 ounces [0.09 kg]). The total weight of the base product/propellant mix should be 16 ounces.

Spark Igniters. A set of direct current (DC) spark igniters must be used to ignite the propellant/base product mix as it is discharged from the pressure vessel. An ignition transformer

capable of providing 10,000 volts output has been found to be suitable for powering the igniters, which should be placed 36 inches (91.4 cm) from the point of discharge. The spark igniter gap should be set at 0.25 inch (0.64 cm).

The procedure for conducting the aerosol simulator test is as follows:

Weight the empty simulator device on a suitable scale. Place the 9.6 ounces (0.27 kg) of ethanol (denatured alcohol) and 3.2 ounces (0.09 kg) of water into the pressure vessel. Transfer 3.2 ounces (0.09 kg) of liquid propane from a storage tank into the pressure vessel. Remove all transfer lines and check final mass. Mount the simulator device in either the forward or aft compartment bulkhead such that discharge is directed into the compartment, across spark igniters. Simulator discharge port and the spark igniter must be 2 feet (60.9 cm) above the compartment floor. Begin heating the pressure vessel to raise the pressure of the contents to 210 ± 5 psi (1448 ± 34.4 kPa). Activate the suppression agent/system. Activate the spark igniters. Release the charged contents into the compartment when the concentration of agent is within ± 0.1% of the minimum design concentration.

## A.4.4 SUPPRESSION SYSTEM DESIGN.

The suppression system design used for these fire tests should be similar to the design intended for use in aircraft. For a gaseous total flood system, the quantity of agent used should be that quantity that will produce the same initial concentration by volume in an empty 2000 cubic foot (56.6-$m^3$) compartment as the initial design concentration that will be demonstrated in the required flight test in the actual aircraft cargo compartment. Some aircraft total flood system designs consist of single-bottle discharges, multiple-bottle discharges at staggered intervals, and single-bottle discharges followed by metered systems that bleed smaller quantities of agent into the compartment to maintain the desired concentration. The compartment volume, leakage rate, and diversion time for the aircraft determines the type of system necessary. There may be situations when the volume, leakage rate, and 30-minute test duration required by these fire tests would not allow for the use of the same system design as is intended for installation in an aircraft. One possible situation could be when the leakage from the actual aircraft cargo compartment is much lower than what is required for the fire test and a single-bottle discharge is sufficient to maintain adequate concentration in the aircraft but not in the fire test article. For this and other situations that require changing the system design, a metered system may be used to maintain adequate concentration of agent. The concentration that should be maintained for the fire test should be the minimum design concentration that the system will demonstrate can be maintained by the required flight test. If a metered system is used in the fire test, the concentration in the compartment after the metered system is started should not be allowed to go higher than 10% above the minimum design concentration. The concentration should be measured at heights of 16″ (40.6 cm), 32.5″ (82.5 cm), and 49″ (124.4 cm) in the middle of the compartment. The design and initial concentrations referenced in this paragraph for the fire test refer to the arithmetic average of the three different probe heights. Note that while an averaging of the Halon concentration measurements is allowed in this Minimum Performance Standard, such an approach will not meet the latest FAA/JAA compliance harmonization activities which require the use of Halon point concentration measurements. The ignition location and the location of the combustible material is well defined for the fire tests required by this standard.

Therefore, the use of an average suppression agent concentration as measured by probes below, above and at the approximate height of the ignition location will give a good indication of the concentration that is actually suppressing the fire. The method of measuring the concentration of agent in the required flight test might not use the arithmetic average of three probes. The certification authority that requires the flight test will specify the number and location of the probes that should be used to determine the concentration of agent in the compartment.

The following FARs are applicable to cargo compartment fire suppression systems:

FAR 25.851(b)(2). The capacity of each required built-in fire extinguishing system must be adequate for any fire likely to occur in the compartment where used, considering the volume of the compartment and the ventilation rate.

FAR 25.855(h). Flight tests must be conducted to show compliance with the provisions of Sec. 25.857 concerning 25.857(c)(3) for the dissipation of the extinguishing agent in Class C compartments.

Halon 1301 and some of the proposed replacement agents for Halon 1301 are significantly heavier than air and tend to stratify fairly shortly after discharge. The location of a fire in the cargo compartment of an in-service aircraft could be anywhere that cargo is placed. The use of an average agent concentration to show compliance with the above FARs would not be appropriate because it would result in agent concentrations in some parts of the compartment that are below the minimum design concentration that has been shown to be effective.

For a nongaseous suppression system, parameters such as activation set points, operating pressures, nozzle spacing and direction, etc. should be the same as the system intended to be installed in the actual aircraft. Other factors that are cargo compartment size dependent such as agent quantity, number of nozzles, zone sizes, etc., should be scaled up or down as appropriate when the volume and/or shape of the compartment in the actual aircraft is different than the 2000-cubic foot (56.6-$m^3$) compartment required for these tests.

## A.4.5 SUPPRESSION SYSTEM ACTIVATION.

Bulk-load, containerized-load and surface-burning fire scenarios: The suppression system should be activated 60 seconds after any one of the ceiling mounted thermocouples equals or exceeds 200°F (93.3°C).

Aerosol can scenario: For a gaseous total flood suppression system, the aerosol can simulator should be activated when the agent concentration 2 feet (60.9 cm) above the compartment floor is at the minimum volumetric design concentration ± 0.1%. The agent concentration must be actually measured during this test. Calculation of agent concentration based on the leakage rate is not permitted. The sampling probe for measuring agent concentration should be 36 inches (91.4 cm) from the exit of the aerosol simulator and less than 18 inches (45.7 cm) from the spark igniters. For a suppression system that is not a total flood gaseous system, the aerosol simulator should be positioned at the most difficult location for that particular system.

A.4.6 TEST DURATION.

The duration of the bulk-load and containerized-load fire scenario tests shall be for 30 minutes after the activation of the suppression system. The surface-burning fire test shall be conducted for 5 minutes from the time the suppression system is activated or until the fire is extinguished, whichever occurs first. The exploding aerosol can test scenario is complete 15 seconds after the release of the aerosol simulator contents.

A.5 ACCEPTANCE CRITERIA.

The acceptance criterion for the bulk load fire scenario is that none of the ceiling or sidewall thermocouples exceed 730°F (387.8°C) starting 30 seconds after the suppression system is initially activated until the end of the test. In addition, the area under the time-temperature curve for the ceiling thermocouple that recorded the highest temperature starting 30 seconds after the suppression system was activated cannot exceed 11900°F-min (6593°C-min). The area should be computed from the time of initial suppression system activation until the end of the 30-minute test duration.

The criteria for the containerized-load fire scenario is that none of the ceiling or sidewall thermocouples exceed 670°F (354.4°C), starting 30 seconds after the suppression system is initially activated. The area under the time-temperature curve cannot exceed 15.400°F-min (8538°C-min). These values for the bulk, containerized, and surface burn fires are based on an approximate 10% increase over the maximum values obtained in a series of tests conducted under the requirements of this MPS using Halon 1301 as the suppression agent. Figure A-9 shows the critical times during a test for computing the acceptance criteria for the bulk and containerized fire scenarios.

The acceptance criteria for the surface-burning fire scenario is that none of the ceiling or sidewall temperatures exceed 1250°F (677°C) starting 30 seconds after the suppression system is initially activated until the end of the test. In addition, the area under the time-temperature curve cannot exceed 3270°F-min (1799°C-min).

The criteria for the aerosol can scenario is that no overpressure should be present in the compartment at the time the simulator is activated.

Five tests must be conducted for each scenario. The suppression system must successfully meet the acceptance criteria for all five tests. Table A-1 summarizes the acceptance criteria for the four fire tests.

TABLE A-1. ACCEPTANCE CRITERIA

| Fire Scenario | Maximum Temp. °F (°C) | Maximum Pressure psi (kPa) | Maximum Temp-Time Area °F-min. (°C-min) | Comments |
|---|---|---|---|---|
| Bulk Load | 730 (387.8) | Not applicable | 11,900 (6,593) | Temperature limit starting 30 seconds after suppression system activation. Temp.-Time area for 30 minutes starting with suppression system activation. |
| Containerized Load | 670 (354.4) | Not applicable | 15,400 (8538) | Temperature limit starting 30 seconds after suppression system activation. Temp.-Time area for 30 minutes starting with suppression system activation. |
| Surface Fire | 1250 (676.7) | Not applicable | 3,270 (1799) | Temperature limit starting 30 seconds after suppression system activation. Temp.-Time area for 5 minutes starting with suppression system activation. |
| Aerosol Can | Not Applicable | 0 | Not applicable | There shall be no explosion |

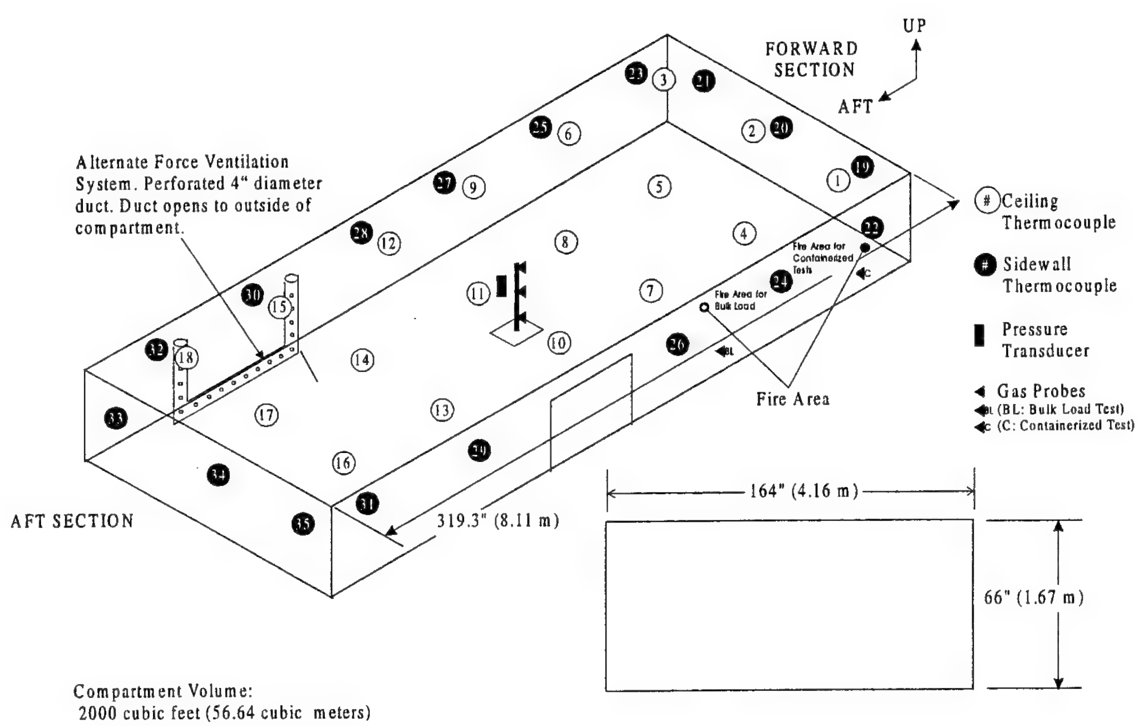


FIGURE A-1. CARGO COMPARTMENT LAYOUT AND INSTRUMENTATION LOCATIONS

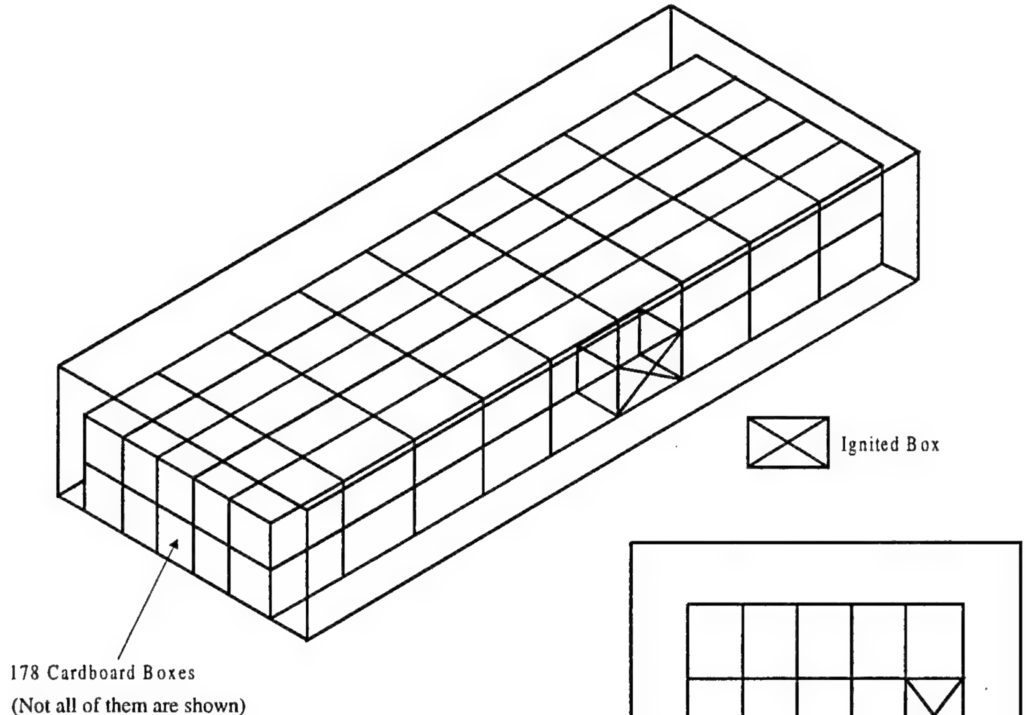


FIGURE A-2. BULK FIRE LOAD TEST SETUP

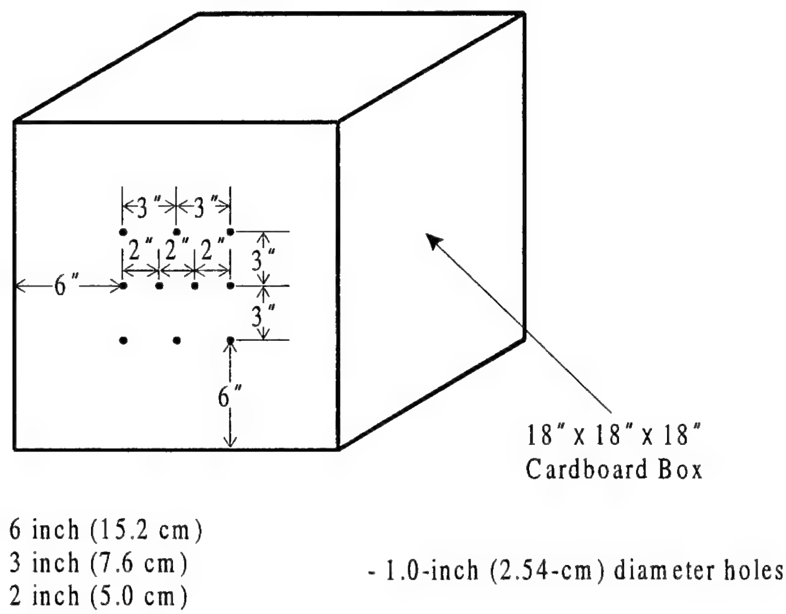


FIGURE A-3. IGNITER BOX

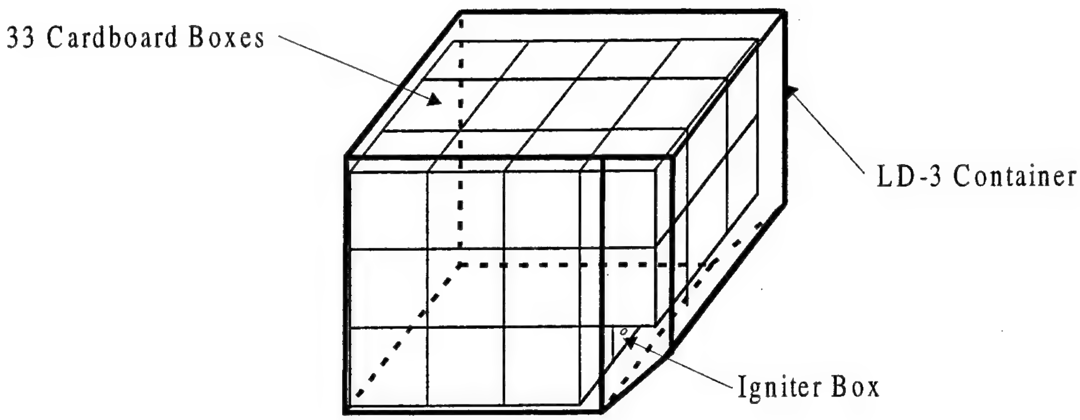


FIGURE A-4. CONTAINERIZED FIRE TEST SETUP

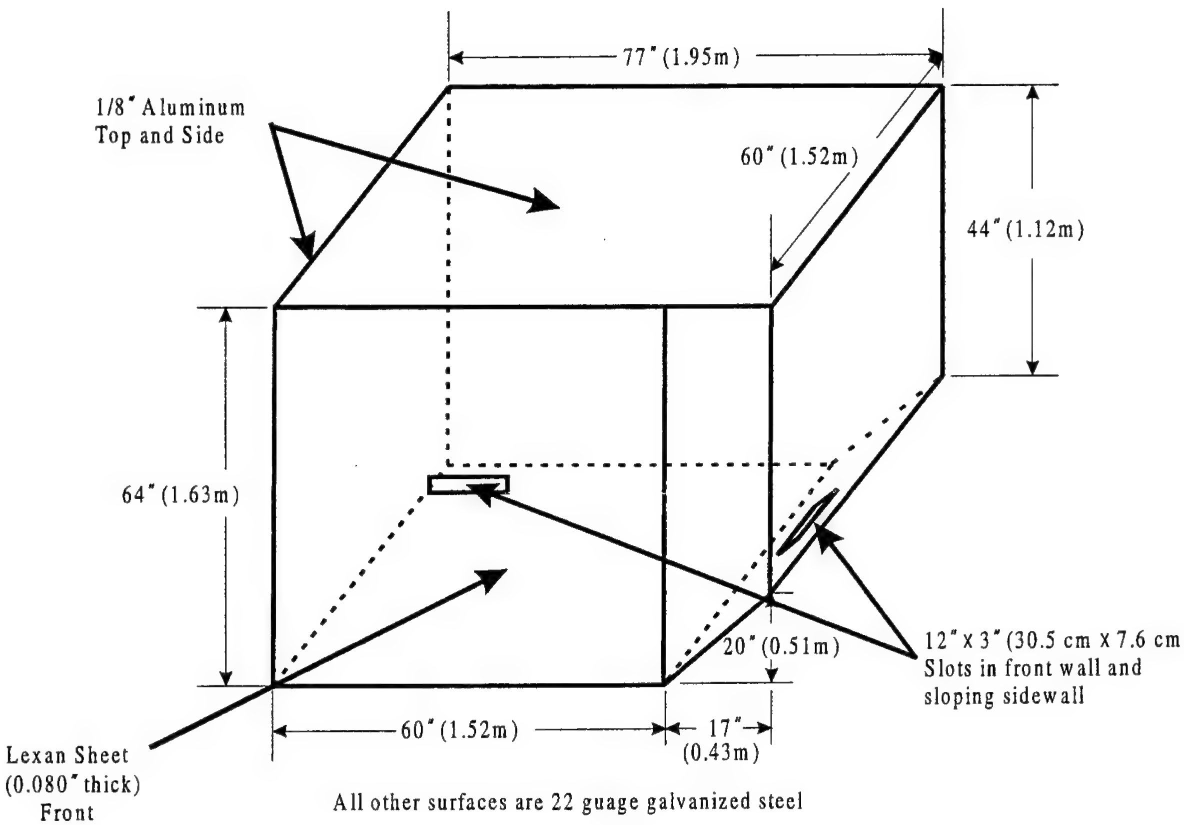


FIGURE A-5. LD-3 CONTAINER

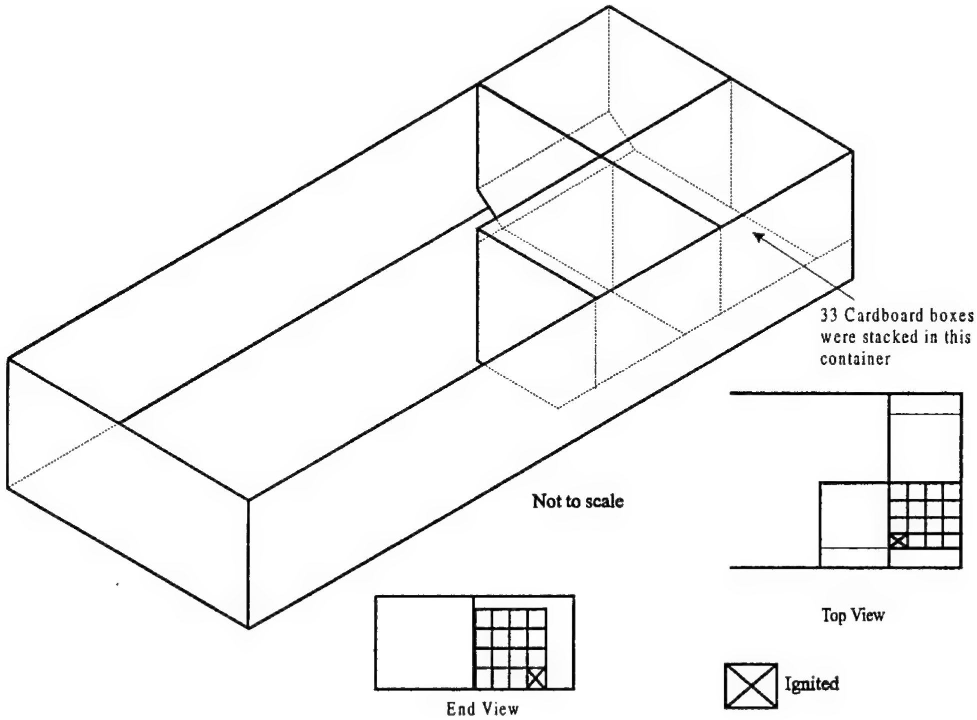


FIGURE A-6. LD-3 CONTAINERS ARRANGEMENT

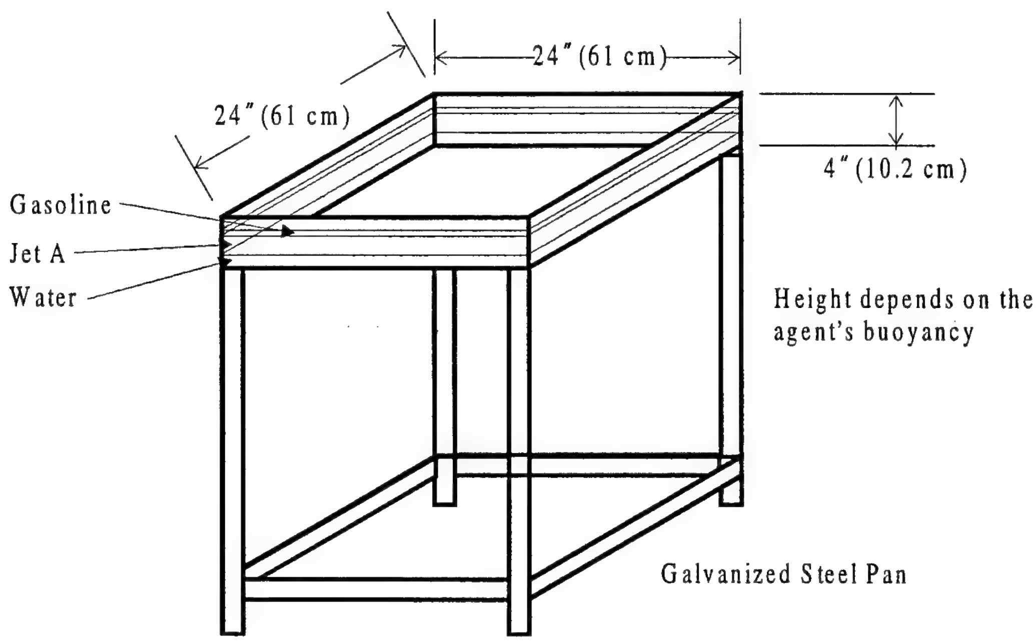


FIGURE A-7. SURFACE BURNING FIRE PAN

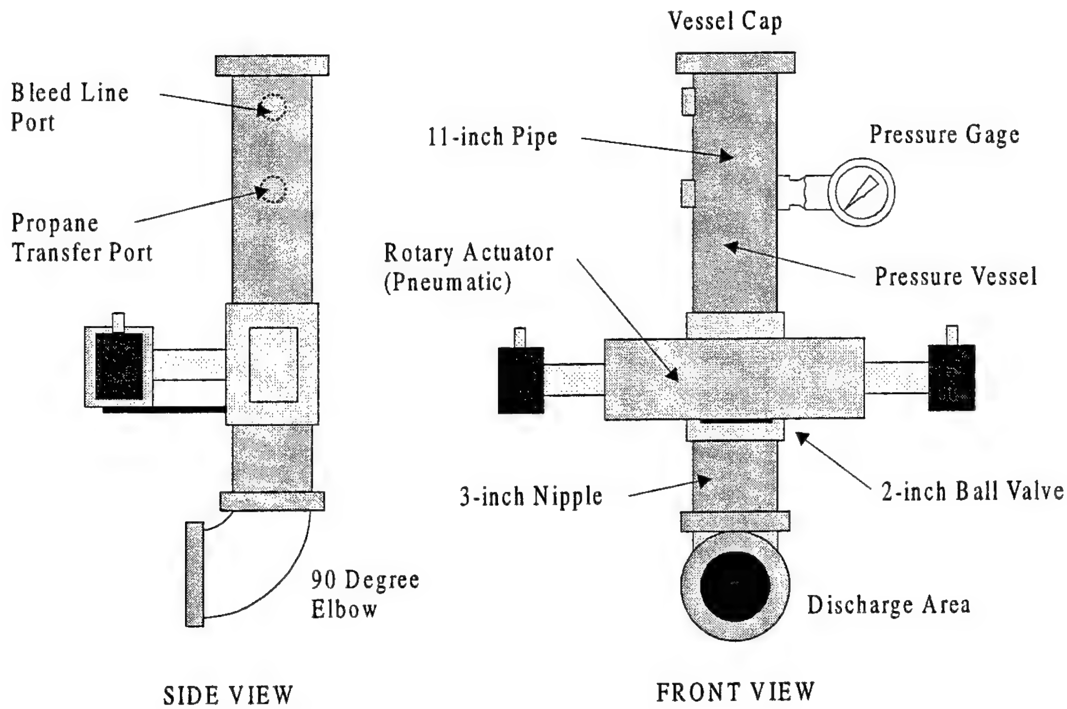


FIGURE A-8. SCHEMATIC OF AEROSOL EXPLOSION SIMULATOR

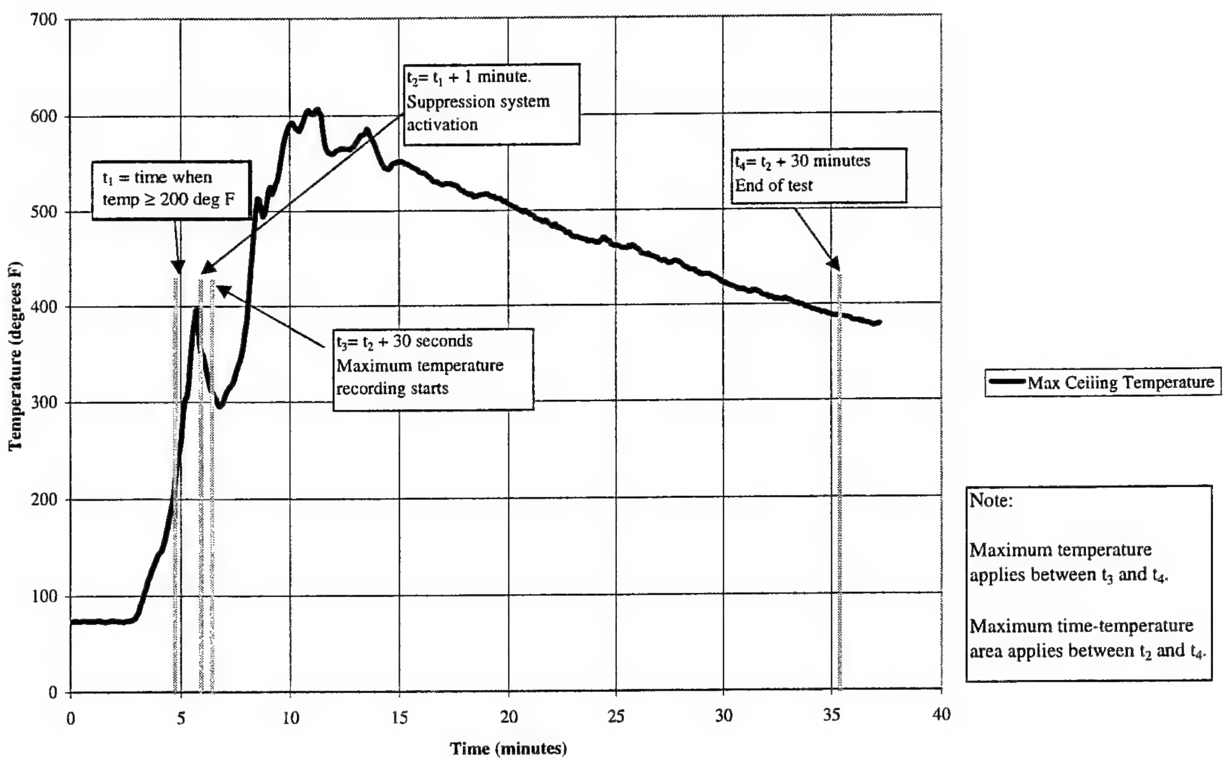


FIGURE A-9. ACCEPTANCE CRITERIA BOUNDARIES

# APPENDIX B—TASK GROUP ON DEVELOPMENT OF A MINIMUM PERFORMANCE STANDARD FOR AIRCRAFT CARGO COMPARTMENT BUILT-IN FIRE SUPPRESSION SYSTEM

This list includes all persons that have participated in the development of the minimum performance standard since October 1993, as some members of the task group have since withdrawn from the task group.


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